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Design for Automated Manufacture of Composite Structures

School of Aerospace, Transport and Manufacturing

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Supervisor: Professor Ashutosh Tiwari
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ABSTRACT

New trends in manufacturing highlight the growing use of composite materials to produce lightweight, high performance structures. This requires the design stage to account for complex manufacturing constraints, and as industry begins to move towards automated manufacturing of composites, the more complex manufacturing constraints can introduce severe limitations to the design space, reducing the opportunity for designers to optimise a product. To address these limitations, this research proposes strategies for implementing design for manufacture specifically accounting for automated manufacture of composite structures.

As a composite design develops, more detail is added, increasing the design fidelity. Typically design for manufacturing practices are only applied when the design fidelity is detailed enough to see individual plies. However, by implementing design for manufacturing practice at earlier stages of the design, when the design fidelity is low and design change is easy to implement, the greatest performance and manufacturing gains can be achieved. This research aims to develop a design process that uses digital technology to facilitate design for automated manufacture for composite structures.

This research uses a systematic approach to create a generic design process and supporting tools, capable of identifying the key manufacturing constraints, and accounting for them at the earliest possible stages of the design. The proposed design process uses a strategy to apply design for manufacture using digital tools, and identifies actions required to enable automated composite manufacturing. The development of the design process is guided by the capture of the current industrial design practices.

The proposed process is validated through the design and manufacture of an industrial demonstration structure, produced using an automated composite manufacturing process. The results from validation confirm the hypothesis that it is possible to have a generic design process to support the design for automated manufacturing of composites components.

Keywords:

Design for manufacture, automated composite manufacture, automated deposition, DFM, FMEA, carbon fibre, design lifecycle.

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L. Veldenz, M. Di Francesco, S. Astwood, G. Dell, B. Chul Kim, and K. Potter, "Characteristics and processability of bindered dry fibre material for automated fibre placement," in ECCM17 - 17th European Conference on Composite Materials, 2016, pp. 1–8.

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LIST OF ABBREVIATIONS

AFP	Automated Fibre Placement
AR	Augmented Reality
ATL	Automatic Tape Layer
CAD	Computer Aided Design
CFRP	Carbon Fibre Reinforced Plastic
DFM	Design For Manufacture
DFX	Design For X, (where 'X' could be any process)
FE	Finite Element
FEA	Finite Element Analysis
FMEA	Failure Mode Effect Analysis
FRP	Fibre Reinforced Plastic
GFRP	Glass Fibre Reinforced Plastic
HiVol	High Volume
KBE	Knowledge Based Engineering
MCL	Minimum Cut Length
MDO	Multi-Disciplinary Optimisation
MDOW	Multi-Disciplinary Optimised Wing
mPDA	Manufacturing Ply Design Analysis tool
NC	Numerical Control
NCC	National Composites Centre
NGCW	Next Generation Composite Wing
NSGA-II	Non-dominated Sorting Genetic Algorithm, version 2
PACKS	Parametric Composite Knowledge System
Pre-Preg	Pre-impregnated material, a type of composite material
RTM	Resin Transfer Moulding
XWB	eXtra Wide Body

1 INTRODUCTION

1.1 Research Context

The aerospace industry is looking towards composite materials as a potential way to reduce aircraft operating cost and improve aircraft performance [1], [2]. The benefits of composite materials such as carbon fibre reinforced plastic (CFRP) enable designers to engineer structures with low mass, reduced part count and with greater flexibility to tailor the structural performance of each composite laminate [3]. However, the use of composite materials for the manufacture of complex products such as an aircraft primary structure, require the designer to account for specific material and manufacturing limitations when the design is created. The design decisions made during aircraft conceptual design often fail to consider the impact that the decisions have on the component manufacture [4], and in many cases, when the design objectives have been set for aircraft performance, many of the solutions produced are unsuitable for real-world manufacturing [5]. The disconnect between concept design and manufacturing of composites is so great, that approximately 80% of the manufacturing costs are fixed based on the design decisions made at the conceptual design stage for a composite component [6].

The trend of changing from metallic structures to composite structures which are made using automated methods, together with the knowledge gained by the author as a result of working for an aerospace research organisation, led to the identification of some major risks for the future of automated composite manufacturing.

The first major risk identified is the threat of too many manufacturing-critical design decisions being made at the early concept stages of the design, without the consideration for manufacturing. As the design maturity increases, it becomes increasingly difficult to implement design changes without affecting component performance or cost [6].

The second risk identified is based on the reliance of digital tools to aid design. The use of these tools enables designers to optimise or improve the component

design with key objectives in mind, but they require user input to utilise manufacturing intelligence to ensure that manufacturing best practices are accounted for [7].

A third risk is that the existing methods and tools used by designers are either biased towards metallic manufacturing processes, or do not adequately consider composite manufacturing, making them misleading. This results in the existing tools being too specific for a component or too generic in their approach [8].

Design for manufacture (DFM) has traditionally been used to describe the process of considering the manufacturing constraints of a particular production process when creating the design, to ensure successful, or improved production of the component. The DFM process requires the manufacturing constraints to be known at the time that the design is created, and this creates two challenges for composites which are linked to the identified risks:

- **Designing for new or novel manufacturing processes:** If the design is using a new or novel manufacturing material or process, and the manufacturing constraints are not fully understood, how can DFM be successfully implemented? A systematic approach to evaluating the manufacturing challenges and then applying the findings to a design is required.
- **Best practice for the use of digital tools:** If the digital tools used to create the design are derived for use with a different material or process, how can they be adapted or used successfully with the new material or process? A strategy for using digital design tools in the context of DFM is required.

The research interest in this thesis is to define a design process that will allow designers to follow a design for manufacture approach to designing composite structures for automated manufacture, and other novel manufacturing processes. The focus of this thesis will follow:

- The best practice for designing for the automated composite manufacture.
- The methodological support needed to adopt a systematic approach for using digital tools and DFM best practices when designing for automated composite manufacture.

1.2 Industrial Motivation

Within the aerospace industry the adoption of composite materials has increased, and aircraft like the Airbus A350 XWB and the Boeing 787 Dreamliner now utilise CFRP for the main wing and fuselage primary structures [9]. Within Airbus, several research programs focused specifically on the use of CFRP to achieve aircraft performance improvements and also reductions in production costs. This thesis was motivated by two Airbus research programmes in particular:

The Airbus HiVol wing research programme evaluated the effects of high-volume production of a CFRP wing [10]. The programme designed a CFRP wing which was manufactured using automated fibre placement (AFP) in a configuration which combined several primary structures into one single component, enabling fewer fasteners to be utilised. The research objective was a design and a manufacturing process that could facilitate a production rate of 80 composite wings per month, while the fastest composite production process at the time was the A350 XWB, which was targeting a production rate of 26 composite wings per month. The results of HiVol showed that the design was not able to be produced at the required manufacturing rate, and a number of design features had to be re-designed just to facilitate the automated manufacturing process.

The Airbus MDOW programme, Multi-Disciplinary Optimised Wing, was a research programme with the objective of rapidly creating and then evaluating aircraft conceptual designs [11]. The programme focused on the theoretical introduction of a new single-aisle aircraft which would be sold in high numbers with a large profit margin. The automated composite manufacturing process

needed to be modelled in a digital tool that could evaluate the manufacturing complexity and indicate the manufacturing cost of a conceptual design. The programme successfully reduced the evaluation of a concept aircraft design from 4 months to 24 hours, which enabled Airbus to evaluate significantly more concepts prior to selecting a design configuration for detailed design, and enabled a number of manufacturing constraints to be applied to aircraft designs at a conceptual stage in the design lifecycle.

Both research programmes highlighted the role that DFM plays in the development of a new aircraft design. The MDOW program highlighted how difficult it is to digitise manufacturing constraints and apply them to a low fidelity design, which is a real-world challenge for anyone looking to influence the 80% of manufacturing costs locked at that low-fidelity conceptual design stage. The HiVol program served as a practical reminder that manufacturing constraints need to be accounted for if the design is going to be manufactured, and that manufacturing speed is directly influenced by design features.

In summary, the lessons learned from these two industrially led research programmes have provided an ideal platform to establish a process for DFM for automated composite manufacturing, and in parallel have provided sufficient complexity to highlight some of the barriers faced in industry to adopting DFM successfully. Because DFM has not adequately been implemented in previous composite aircraft programmes, there is now a significant interest from aerospace companies in the methodology of how to exploit DFM successfully for composite structures. This thesis aims to contribute to this requirement by building further understanding of the role of automated composite manufacturing constraints in the DFM research literature.

1.3 Research aim and objectives

The aim of this research is “to develop a generic process that uses digital technology to facilitate design for automated manufacture for composite structures”. A list of specific objectives which are required to fulfil this main aim are:

1. Capture the state of the art for DFM of composites using digital technologies.
2. Capture the current industrial design practices using use cases for composite structures.
3. Develop strategies for applying DFM best practice through the use of digital tools.
4. Develop a generic process and supporting tools to systematically apply DFM for automated composite manufacture.
5. Validate the proposed DFM tool kit using a design use-case described in section 1.6 “Research Methodology”.

The two industrial research projects identified in section 1.2 would have benefited from the correct use of digital tools and a more systematic approach to accounting for manufacturing constraints. The first two objectives will help to explore the context of the research problem in greater detail, while objectives 3 and 4 aim to provide a better process for engineers to follow to ensure that all of the relevant DFM questions are asked at the correct stage in the design lifecycle.

In conjunction, all of the objectives can be combined to demonstrate true DFM for automated composite manufacture.

1.4 Hypothesis

The achievement of the research objectives will confirm the hypothesis that it is possible to have a generic design process to support the design for automated manufacturing of composites components.

1.5 Research approach

The author has researched this topic on a part-time basis while being full-time employed by a research organisation, specifically tasked with researching the overall theme of this thesis. The research methodology therefore reflects an action-research approach, being initiated by industry to address a known problem, and featuring elements of both participation research and practical research enabling a solution to be created.

In this research, design is fundamentally considered to have a lifecycle, starting with the formation of an idea, and progressing as the idea develops an identity in the format of a design, increasing in maturity and fidelity as it develops towards a physical manufactured product. When the whole lifecycle of a design is considered, the notion of considering the final manufacturing constraints at the early stages in its lifecycle, or maturity, while all the design freedom is yet to be narrowed down, is often considered impractical. Yet failure to properly account for essential constraints routinely causes unwanted design evolution later in the design lifecycle and often at great cost. It is therefore important to consider the validity of any DFM action for a given point in the design lifecycle, so that it is not being applied infeasibly early, or impractically late in the design's maturity.

Being able to ensure that an engineer applies DFM best practice at the right stage in the design lifecycle is challenging. The challenge increases when the DFM best practice itself is not adequately documented, or the manufacturing process is novel or not fully understood.

In order to address the challenges around the design lifecycle and the application of DFM for automated composite manufacture, the research focuses on three key areas:

- Understanding the problem and finding or defining the right DFM best practice. Linked to objectives 1 and 2.
- Establishing where in the lifecycle to get the most value from it, and how to apply it to the design. Linked to objectives 3 and 4.
- Validate the proposed process and quantify the benefits. Linked to objective 5.

Consequently, it is important to be able to compare the research findings from published literature with use-cases from industry to evaluate how the research findings can be industrialised.

1.6 Research methodology

The proposed research methodology follows an eight step approach: Problem description, literature review, research gap analysis, industrial best practice review, strategy development, use case validation, conclusions and discussion.

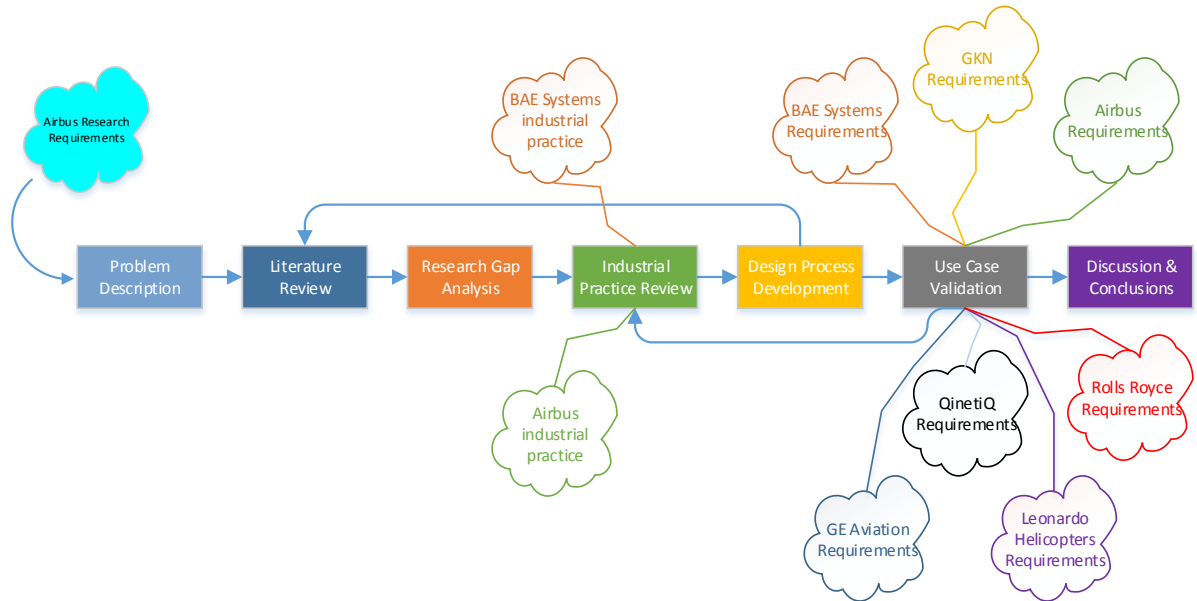


Figure 1: Flowchart of research methodology, showing requirements captured from the NCC's industrial partners

- **Problem description:** At this stage the research problem is defined. The definition focuses on a set of industrially based design challenges that have manifested in the aircraft design research programmes at Airbus. Two factors influenced the selection of the problem description. Firstly, Airbus commissioned this research as an industrially sponsored activity provided that the problem description was of interest to the business. Secondly, the UK's Technology Strategy Board launched two key collaborative research projects, described in section 1.2, which enabled the problem description to be aligned with ongoing research programmes.

- **Literature review:** This stage evaluates the published literature investigated under three main research themes: Design or Manufacture of composite structures, aiming to identify key design or manufacturing best practice related to composite structures. This search string was chosen because existing research focusing solely on design can impact manufacturing, and research focusing on manufacturing often relates to the design. The intention of this search was to return articles that may offer insight into DFM, but without necessarily identifying themselves as DFM articles. DFM of composite structures was used as the second main search string, aiming to identify research which specifically targets DFM principles associated with composites that consider both design and manufacturing phases of the lifecycle. This search is intended to return articles that identify themselves as DFM focused rather than the articles from the first search which made no claim to focus on DFM. The third main search string was digital tools to support DFM, which identifies design tools that have been reported in literature as being used for DFM, albeit not specifically for composite structures. The intention of this search was to target DFM articles that describe digital tools rather than DFM articles that describe processes because the industrial requirements to use DFM dictate the use of digital tools. The articles returned should therefore incorporate research into the practicalities of adopting DFM for a digitised design lifecycle. The results from these research themes are compared to highlight research trends based on the topics that link to the industrial motivation. The research is conducted by using several research search tools described in section 2.1.1, and varying the main search strings to account for alternative spelling and terminology as described in section 2.1.2.
- **Research gap analysis:** This stage evaluates the information found in the literature review to highlight evidence of the main research issues, resulting in the identification of a research gap. The research gap from literature is then assessed by a group of industrial experts to further consolidate the research gap identified, and suggest opportunities and

priorities for the development of a strategy. A visual way of identifying the research gap was implemented, using comparative matrices to highlight what topics each research article covered relative to the research classifications. This approach was chosen because it quantified the key trends by counting the relevant articles. The decision to involve industrial experts was based on a requirement to peer review any key research conclusions at this stage in the research.

- **Industrial practice review:** In order to capture the methods, tools and knowledge residing in industry, which have not been published in literature, the industrial best practice for designing composite structures for automated production are recorded and discussed. The industrial practice first had to be identified, and then reported. To enable this, several use cases were designed based on industrially relevant content generated in a number of different Airbus research programmes. These use cases are used to explain and demonstrate key industrial practices relating to the design and manufacture of composite structures. The use cases are provided in section 3.3.
- **Design process development:** At this stage, the methods, tools and decision guidance required to achieve the research aims were developed. To start with, a systematic approach for analysing the design steps was required, enabling a uniform and consistent system to query each design step. The formation of the design guidance was aided by progressing through the entire design lifecycle, resulting in a detailed process flow that audits the decisions and manufacturing knowledge required to successfully implement a DFM approach. During the development of a generic design process, additional searches of previously published literature were carried out to identify any useful approaches for assessing the design lifecycle in a systematic fashion. This loop back to the literature review is illustrated in Figure 1.
- **Use case validation:** In order to comprehensively test the DFM strategy and the generic process flow, an industrial use case was created. The use case embodies the key characteristics of multiple aerospace and

automotive composite structures, with features specifically chosen to highlight the challenges of producing composite structures using automated technology. The use case component is taken from conceptual design, through to physical manufacture using an automated fibre placement machine (AFP), allowing the proposed DFM strategy to be validated. The use case component design and manufacture was funded by the National Composites Centre (NCC), as part of a collaborative research program with a number of OEM and tier 1 aerospace businesses. Each of the businesses was required to propose geometrical features and manufacturing parameters that represented a challenge to their business. This helped to ensure that the design features were industrially relevant, and representative of realistic industrial challenges. By selecting this use case it is possible to address the requirements of several leading aerospace businesses. Throughout the design and manufacture of the use case component and sub-scale trials the progress was reported to the NCC and the collaborative research businesses to enable review and feedback to be incorporated.

- **Discussion & Conclusions:** Upon successful validation of the use case, the conclusions and discussion were reported. This stage discusses the research key findings and evaluates the quality and applicability of the results. In these sections, the limitations of the research are discussed and the next steps for the research suggested,

1.7 Contribution to knowledge

This research describes the process of designing a composite structure so that automated manufacturing can be utilised, and it proposes a systematic process that engineers can follow to guide them through the application of DFM when dealing with a novel manufacturing process. The contribution to knowledge occurs in two key areas:

- 1) Capturing and recording industry practice for DFM of composite structures for automated manufacturing. The process flow and detailed design steps for creating manufacturable designs has not been

sufficiently recorded in published literature. A number of previous research articles describe DFM for composites specifically around isolated design activities, or specific manual manufacturing processes, however these articles do not cumulatively describe all of the DFM design steps needed to manufacture a composite structure, and existing articles cannot be combined to describe how to design for an automated composite production process. This will be the first time that the state of the art for DFM of composite structures for automated manufacturing has been recorded.

- 2) Defining a generic design process for applying DFM to the design lifecycle when the manufacturing process is not mature. This research delivers a process which engineers can follow when they are responsible for creating a design, but do not have sufficient manufacturing knowledge available to them. The process will prompt them to identify the key manufacturing constraints sufficiently early in the design lifecycle. This will be the first time that the application of DFM for automated composite manufacturing has been recorded in sufficient detail to enable a generic design process to be described.

As a result, this research enables engineering design teams to:

- **Identify key manufacturing constraints:** by following a systematic approach to evaluate the manufacturing process relative to the design steps.
- **Implement DFM for automated manufacture of composites:** by following the design process flow provided.
- **Improve the manufacturability of a composite design:** by understanding how the design decisions influence the manufacturing process.
- **Digitise tools to improve manufacturability:** by quantifying what constitutes good composite manufacturing and embedding the knowledge within digital design tools.

1.8 Thesis structure

This section summarises each chapter of the thesis to enable the reader to understand and navigate the document.

- **Chapter 1:** Describes the challenges faced by engineers in industry aspiring to apply DFM to composite designs which are destined for automated manufacture. The chapter describes the hypothesis on which the research is based, the research aims, objectives and approach required to address these research aims, and also the research methodology. The chapter concludes with a definition of how the research is contributing to knowledge.
- **Chapter 2:** Describes the literature survey carried out to establish the state of the art for composite DFM. The chapter breaks the literature survey into three main sections, design and manufacturing of composites, design for manufacture of composite structures, and digital tools for DFM. The research trends are discussed and the research gap identified is proposed.
- **Chapter 3:** Describes industrial practice captured by the author while working on the development of a number of composite aircraft programmes. The chapter uses industrial use-cases to demonstrate the design practices for several stages of the design lifecycle specifically focusing on the sizing of a composite structure, the manufacturing analysis performed and the design evaluation methods.
- **Chapter 4:** Describes the strategies that can be used to apply DFM using digital tools. The chapter describes several methods for evaluating a preliminary design such as generating a ply continuity score and a ply complexity score. The methods are described using industrial use cases, and the methods are tested and validated on four sample composite coupons which are evaluated as preliminary designs, then detail-designed, manufacturing process simulated and then finally physically manufactured using an AFP machine. The cycle times of the simulation and physical manufacture are compared to the design evaluation scores generated from the preliminary design to validate the approach.

- **Chapter 5:** Describes the design process and supporting tools for applying DFM. The chapter describes how a systematic approach to control the ambiguity of conflicting design and manufacturing objectives is required, and proposes the use of a failure mode, effect analysis approach, FMEA. The proposed design method is described as a process flow, as a table of discrete design steps and then in detail for three use cases specific to composite structures being manufactured using an AFP machine: The first use case example is a flat panel with a pad-up of increased material thickness surrounding a hole, with the AFP manufacturing constraint of minimum cut length applied. The second use case looks at the effects of short fibres on a corner laminate. The third use case focuses on the manufacturing problems that the AFP process causes when an area of the laminate is over-consolidated, and how the design can be adapted to reduce the effects of this problem.
- **Chapter 6:** Describes the use case and validation exercises carried out to support this thesis. The chapter describes an industrial demonstration component as a use case. The component is taken through the entire design lifecycle from a conceptual design through to a physically manufactured structure using the dry-fibre AFP manufacturing process. The design process and digital tools described in previous chapters are used to ensure a design for manufacture approach is adopted for all stages of the design. At each design stage, the manufacturing intelligence added by the proposed design process is identified and the benefits are described.
- **Chapter 7:** Describes the discussion and conclusions based on the research results. The chapter describes the research achievements, including research quality, generality and applicability achieved. The key research limitations are identified, and future work is proposed. The final section concludes how the original industrial motivations have been addressed with this research.

- **Chapter 8:** Lists the additional information provided in the appendices. The generic design process described in chapter 5 is broken into each of the individual steps, which are described in detail as they were evaluated using the FMEA technique.

2 LITERATURE REVIEW

This chapter contains the literature survey which was carried out to understand the state of the art for composite structure design and manufacturing. The literature reviewed varied greatly in the degree of application achieved, with some articles focusing on very narrow segments of the design lifecycle, and others covering multiple lifecycle stages. Since the challenges described in section 1.1 appear to propagate in the early stages of the design lifecycle but manifest in the later stages, special attention was paid to research that spanned multiple design lifecycle stages.

The literature review has focused on the existing contributions to knowledge in the field of DFM for automated composite production, and also on the contributions to knowledge of other research in different domains which could potentially be applied to DFM for automated composite production.

The literature review is presented as a series of comparisons between the research theme and the way in which it could potentially be applied to address the research aims.

This chapter is structured to start with a description of the survey approach used in section 2.1, a description of the background or theoretical foundations of the review in section 2.2, then in section 2.3, 2.4 and 2.5 the key research findings are presented, with an analysis of how these findings influence this research work. The identification of the research gap is described in section 2.7. The concluding remarks are addressed in section 2.8.

2.1 Survey approach

The initial research scope was generated by the author based on three risks that were identified in section 1.1. This led to three areas of initial interest, and a fourth risk was identified later in the research. These risks are illustrated in Figure 2:

- 1) Research related to the design or manufacture of composite structures,
- 2) Research related to DFM processes and,
- 3) Research into the use of digital tools to aid DFM.
- 4) Research related to the systematic approach required to evaluate a design

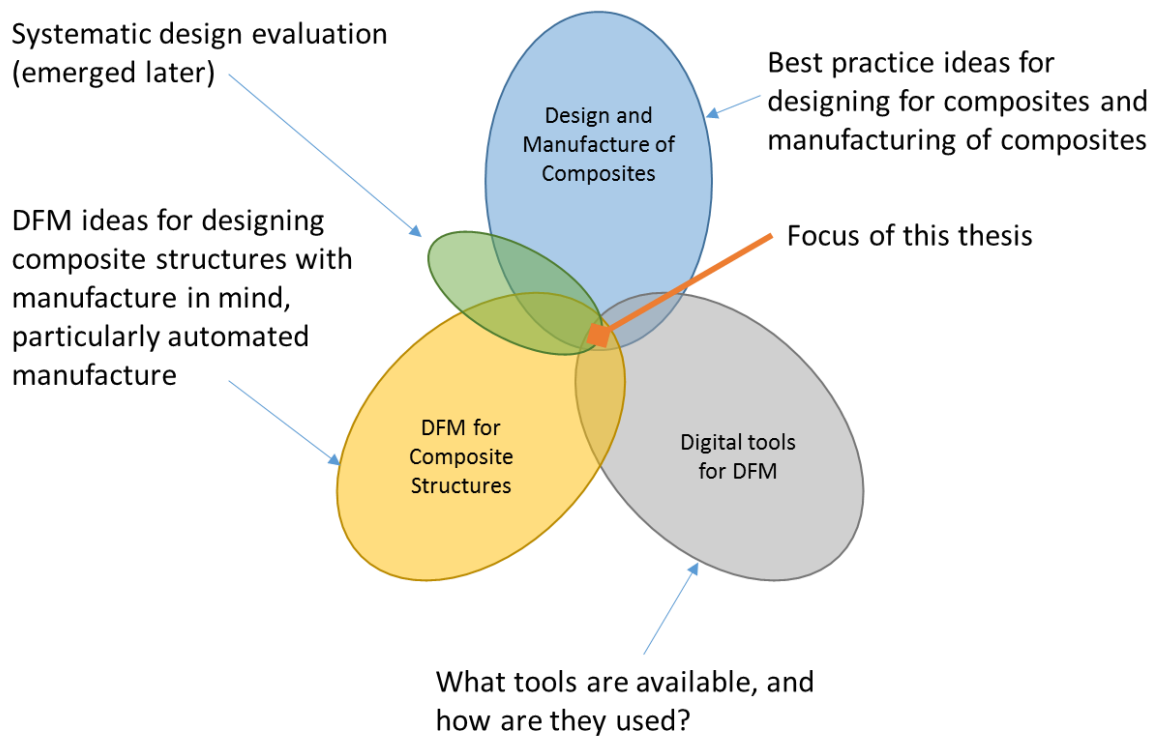


Figure 2: Venn diagram showing three initial research aspects for DFM for automated composite manufacture, and the fourth, coloured green, which emerged later in the research

A fourth area of interest emerged after the initial research scope had been fulfilled, when a systematic approach was required to apply a DFM approach to a new composite structure design. This area of interest is described in section 2.6.

Context was required so that the relevance to both the industrial motivation and research problem could be discussed, and this formed the research background upon which the research key trends could be established.

By analysing the trends in the reviewed research, the research gap analysis was carried out. This indicated both where further research was required, and also where existing research could be utilised to help deliver the research objectives.

The literature searches were carried out predominantly using the Scopus research search tool, but supplemented with information obtained using Google Scholar and unpublished research libraries found at Airbus Group and at the National Composites Centre.

2.1.1 Data collection process followed

The literature search was carried out using two main techniques. Firstly, a structured literature search was carried out using a variety of external databases such as Scopus, Science Direct, Sage and Google Scholar. Google web search was also used to provide press articles relating to industrial tools and processes. These web based articles were identified by searching for the tools and processes described in journal and conference articles. The second technique was less structured, with references and citations made within interesting papers being investigated as potential sources of relevant material. In addition, articles that the author uncovered during the course of daily work at Airbus Group Innovations and the National Composite Centre were included if they contributed to the research scope.

The search was started by defining a set of keywords which support the research scope. These keywords were used in the initial phase of the search, such as “Design for Manufacture of Composites” and “Digital tools for DFM”. These initial searches returned a large number of results, and to facilitate the discovery of significant articles, several additional searches were carried out using combinations of associated keywords.

For instance, a Scopus search for “Design and Manufacture of Composite Structures” carried out in 2012, returned 1058 articles. Removing the key word “structures” increased the number of results to 2752. To improve the significance of the search results a number of search filters were applied.

Excluding non-relevant sectors such as medicine and biology, only displaying conference papers and journal articles, and filtering to only return English language articles reduced the search to 797 results.

When manually screening the search results, which have already been ordered by relevance, it became clear that for almost all cases the relevance deteriorated beyond the point of interest after approximately 400 articles. For instance, titles that clearly identified a topic that was not of interest, such as “Stress analysis in ceramic inlays restored premolars” appearing after 200 articles in the results list, could be rejected as too specific without the need to read the abstract or full paper. Whereas “Object-oriented implementation of an integrated design and analysis tool for fiber placed structures” by Schueler, K.& Hale, R. [12], appears relevant to the research scope and the abstract described a project very similar to an Airbus industrial project initiated in 2012.

Only articles with relevant content were stored and classified in any of the comparison matrices presented in this thesis. Content which relates to the automated deposition process and associated design implications is very relevant, and an example is illustrated in Figure 3. The automated deposition process illustrated is automated fibre placement (AFP), and strips of composite material referred to as tows, are fed onto a conformable compaction roller. The roller position and behaviour is numerically controlled. The material is delivered to the compaction roller through a cutting system, enabling the material deposited to be cut to suit the design. This is illustrated in Figure 4.



Figure 3: AFP machine depositing carbon fibre tapes onto a corner laminate

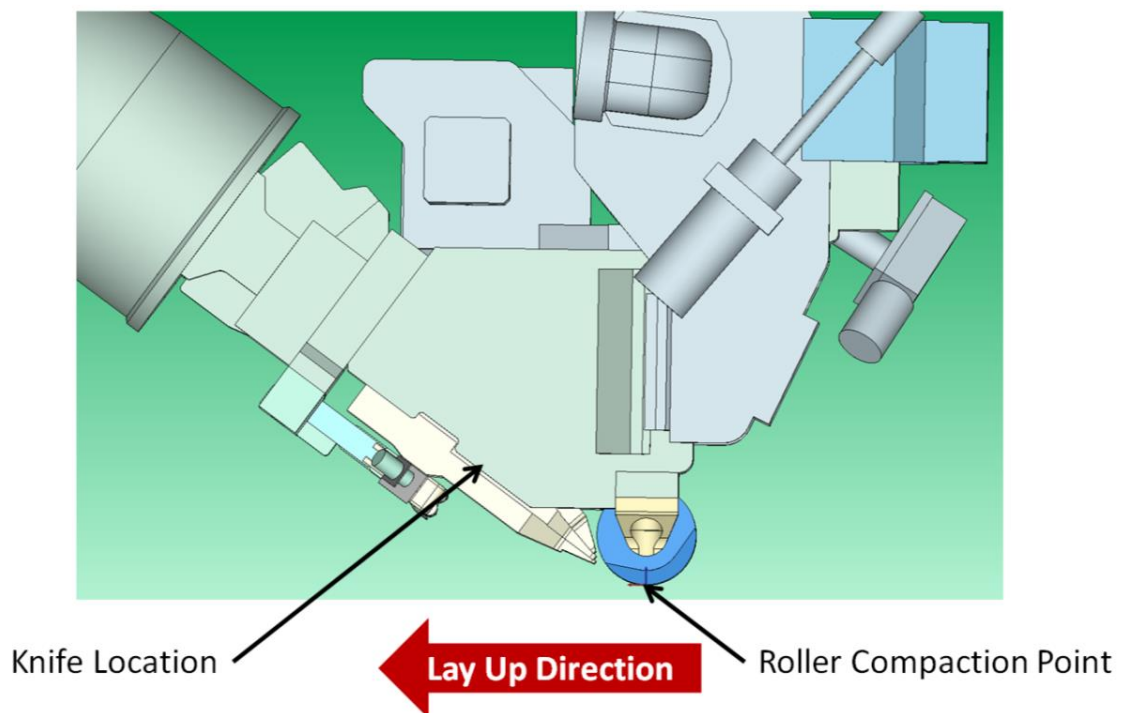


Figure 4: Schematic of how material is fed through a cutting knife onto a compaction roller in a typical AFP machine

2.1.2 Table of key words used in searches

Table 1 presents keywords used in the searches described in sections 2.3, 2.4 & 2.5.

Table 1: Keywords used in literature searches

Keywords	
Design and Manufacture of Composites	Composite Design, Composite Manufacturing, Composite Structures, Carbon Fibre Reinforced Plastic, Fibre Reinforced Plastic, Glass Fibre Reinforced Plastic
DFM for Composite Structures	Design for Manufacture, DFM, Composite Structures, Design for X
Digital Tools for DFM	Design Software, Multi-Disciplinary Optimisation, Composite Manufacturing Constraints, Design Rules

2.2 Background

This section presents a review of the initial background research gathered before focusing on the more specific topics identified in section 2.1. In the search for research in the field of composite structural design, a number of articles that had been commissioned by software vendors were identified. These articles proposed a market study or case study in which their product was compared to other available solutions, and typically concluded that their own product was addressing a niche composite design problem. After initially dismissing these articles as too biased, and lacking peer review, two interesting points became evident:

- 1) The majority of the articles either compared automated composite manufacturing processes, or compared the application of composites materials as a design improvement.

- 2) The age of the articles suggests that automated composite production is the longest running theme, with multi-objective optimisation becoming a trend in 2009, and the most recent articles describing an industry shift from metals to composite materials.

These two basic points reinforce the objectives of both the HiVol project and the MDOW project described in section 1.2, highlighting that the aerospace industry is moving away from metallic structures in favour of composite materials, and that both design optimisation and automation are going to be important in future aircraft designs. The articles are tabulated in Table 2 to highlight the distribution.

Table 2: General composites research articles

Type of Article	Article Topic			
	Comparison of Digital Tools	Exploitation of Optimisation	Application of Composite Materials	Comparison of Automated Processes
Market Study	[13]		[14] [15] [16]	[17] [18] [19] [20] [21]
Case Study		[22] [23] [24]	[25]	[26]

A recent article presented by the Vice President of Research & Technology at Airbus, Jens Grafts [27], clearly explains the vision of how Airbus intend to use automated manufacturing technologies and highly digitised applications to produce their future aircraft. As part of this presentation, Jens highlights the trend in manufacturing rate of an aircraft increasing, but the cost decreasing, enabled by a combination of design for higher rate manufacture, and also the development of better digital tools and autonomous manufacture. This vision is illustrated in Figure 5, showing automated mechanical aids, cobot robots who can work cooperatively with workers and wearable technology.



Figure 5: Airbus vision of the future factory including cobotic assistance and high levels of automation

Further research into the specific fields of design and manufacture of composites, DFM for composite structures and the digital tools used was required to identify the state of the art already established. Cumulatively, these research topics all contribute towards enabling DFM for automated manufacture of composites. The Venn diagram illustrated in Figure 2 shows these three research search themes, with the central overlap representing the area of specific interest.

2.3 Design and manufacture of composites

This section provides the reader with a better understanding of the existing research which focuses on the design or manufacture of composites, where a

potential improvement to the design or manufacturing part of the lifecycle is described. The nature of the proposed improvements in these articles can be compared to identify the research trends, whilst also gathering ideas for managing the improvements.

2.3.1 Background related to composites

Composite materials are not considered to be isotropic like metallic and plastic materials, and their internal structures can be biased to perform and behave differently in different directions. From a design perspective, this enables a designer to exploit the non-isotropic properties to better address the design intent, but from a manufacturing perspective, the additive way in which the material is constructed, typically increases the manufacturing complexity. An example of this is shown in Figure 6 which shows a composite laminate that has fibres steered around a feature to improve load bearing performance.

The design articles and the manufacturing articles can therefore be separated into two groups. The design articles address the practicalities of how to exploit the composite materials to improve the design performance, and the manufacturing articles address the challenges associated with producing designs from composite materials.

2.3.2 Review of composite design improvements

The research identified for the topic of composite design improvements fell into four main themes: Optimising designs for vibration characteristics, optimising a design to reduce uncertainty, addressing the needs of physical testing to validate a design, and a more general theme around general design optimisation which included topics like topology optimisation, structural optimisation and aerodynamic optimisation.

Optimisation of vibration characteristics: One article was found which described the benefits of using composites in conjunction with metals to create hybrid structures [28]. In the article, the benefits of a low-mass machine tool that damps vibration during the cutting process are described, with the low-mass and high stiffness qualities being achieved through the application of composite

materials. Whilst not strictly related to the aerospace industry, this article drew some very useful conclusions about the vibration damping characteristics of composite materials which may need to be considered when designing a composite structure.

Optimising to reduce design uncertainty: Two interesting articles were found in this theme, with the first paper proposing the use of a sensitivity analysis of the design variables and non-design variables to help a designer to build a robust and optimum design problem [29]. The second interesting article proposes the allocation of a robustness index to laminate stacking sequences so that they can be scored and evaluated for damage tolerance [30].

Physical testing to validate designs: One article was found addressing concerns over the low confidence found in low-cost composite manufacturing processes. In this article a method for using physical testing to improve confidence in specific designs is discussed, and the method is validated by manufacturing a number of demonstration components and physically testing them destructively to validate failure predictions from a digital toolset [31].

General design optimisation: Most of the design articles were classified under this theme, with a number of interesting design methods being proposed. In design sequence order, the first article addresses concept design by creating a low-computational tool which can be used to down-select design options prior to investing in evaluation using a high-computational tool [32]. The next article describes the use of analytical modelling methods to attempt to simplify the process of designing with the objective of optimising for torsion and bending loads in a structure [33]. A similar article describes the way in which a composite structure can be tailored to reflect torsion and bending by steering the composite fibres to align them with the calculated load paths [34]. Also discussing the deposition of tailored fibres, the use of a response surface to optimise process parameters is discussed in an article that focusses on the thermoplastic tow placement process [35]. In this paper the speed, heat and pressure parameters for a robotic AFP machine are compared to the quality of the manufactured component to enable a designer to specify optimised design parameters.

Another article related to laminate quality looks at the semi-automated process of braiding, and discusses the benefits of tailoring the ratio of fibre to resin in the finished product to suit the structural requirements of the part [36]. The most interesting article of this collection describes how to carry out a manufacturability analysis during preliminary design, but increasing the design fidelity to model the fibre paths for composite tows, rather than assuming blanket ply coverage as is typical for preliminary designs [12]. The article describes a way to model tow positions in the design and evaluate them using an FEA package, but the work only enables the designer to more accurately control the fibre trajectories, and does not prevent the designer from modelling trajectories that are impossible to manufacture. Another article which linked preliminary design to an FEA tool focused on the idea of using a design of experiments methodology to build a parametric design study, the study would then validate laminate quality by calculating spring-in distortion using an FEA tool [37]. The final two articles in this theme address the use of multi-disciplinary optimisation, with one article reducing cost by the consideration of manufacturing at the same time as design [38], and the other article looking at using multi-objective optimisation to handle the conflicting constraints in laminate stacking sequences [39]. Both of these articles are interesting because they feature concepts that begin to address manufacturing constraints at a design stage of the product lifecycle.

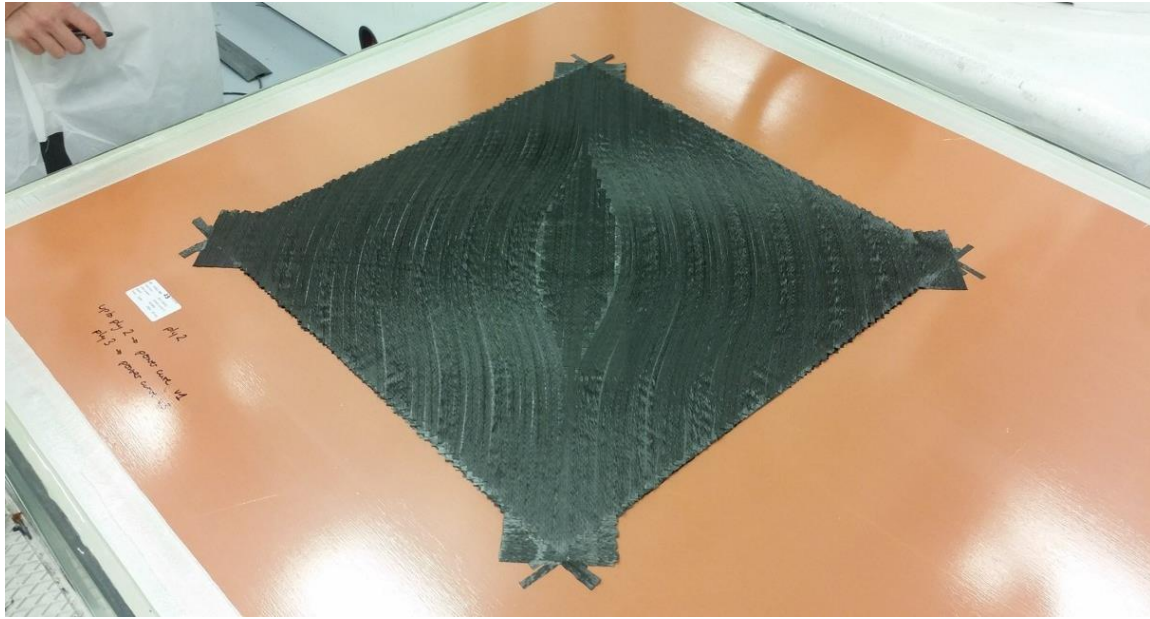


Figure 6: AFP preform with optimised fibre steering for load transfer around a feature. Corners of laminate exhibit material extensions due to minimum cut length of material, specific to the AFP process.

2.3.3 Review of composite manufacturing improvements

The research identified for the topic of composite manufacturing improvements fell into three main areas: Manufacturing process driven design changes, Implementation of low-cost manufacturing processes, and manufacturing process simulation.

Manufacturing process driven design changes: One article was found in this area, and it describes one of the main challenges of this research topic. The article suggests that the manufacturing process needs to be selected before the design is finalised so that the advantages and disadvantages of each particular manufacturing process can be incorporated into the design, preventing the designer from introducing features that preclude the use of desirable low-cost manufacturing processes [40].

Implementation of low-cost manufacturing processes: All of the articles linked to this theme involved the suggestion and evaluation of a substitute manufacturing process that is perceived to be cheaper to run than the baseline composite process. The first proposes the use of a very low cost AFP system

as an alternative to traditional AFP systems [41], the second proposes the adoption of a single-shot resin infusion process instead of autoclave curing pre-preg [42], and the third article suggest the re-design of a component to use of out-of-autoclave materials instead of traditional pre-preg materials [43].

Manufacturing process simulation: Most of the manufacturing improvement articles fall into this theme, with a varied selection of manufacturing process simulations described. For example, the steering analysis of an AFP design is a form of manufacturing process simulation and is illustrated in Figure 7:

- Draping simulation combined with cost estimation [44]. The draping simulation is carried out using FEA tools, and costing estimated using a separate tool to create a theoretical cost/mass optimisation framework.
- Theoretical modelling of the heating process, cooling process, inter-laminar bond strength, fibre compaction load and thermal residual stress [45]. The model of these parameters can be used to aid in the prediction of component quality for thermoplastic AFP components.
- Environmental simulation [46], to model the behaviour of thermoplastic materials when processed at very high temperatures.
- Modelling of draping and consolidation for complex preforms [47] and also for tow placement [48].
- Modelling of variable fibre angles within a laminate [49], to improve structural performance and model subsequent manufacturing defects.
- Simulation of fibre/tow steering [50], but with the addition of co-mingled fabrics to aid manufacture.
- Cost and mass simulation [51], using CAD data to obtain surface geometry and volumetrically calculating component cost.

The articles described in section 2.3 can be categorised by the methods they describe, and the problems they claim to address. This is shown in Table 3.

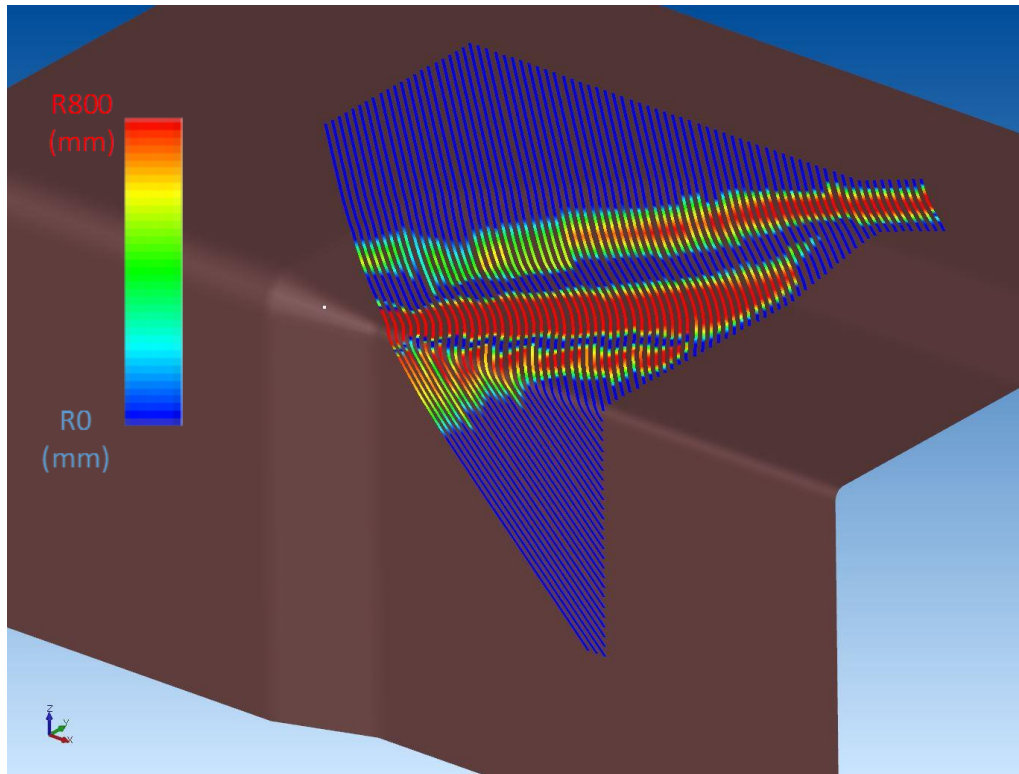


Figure 7: Steering analysis in an AFP manufacturing simulation. Degree of steering is indicated by the colour of the fibre path.

Table 3: Design and manufacturing of composites articles classified by method and problem

Problems Addressed	Methods Described						
	Design Improvement				Manufacturing Improvement		
	Vibration optimisation	Physical testing	Design uncertainty	General design optimisation	Process driven design	Low-cost manufacture	Process simulation
Improve existing design	[28]		[29]	[36] [35] [12] [32] [33] [34]	[40]		[47] [49] [50] [48]
Improve manufacturing confidence		[31]	[30]				[45]
Reduce component cost				[38] [39]		[41] [42] [43]	[44] [51]
Improve component quality				[37]			[46]

2.4 DFM for composite structures

This section provides the reader with a better understanding of the existing research which focuses on DFM for composites. This theme differs from section 2.3 because design-for-manufacture requires manufacturing to be considered during the design process, whereas the research identified in section 2.3 considers design or manufacturing activities to occur at separate stages in the design lifecycle.

2.4.1 Background on DFM for composites

Composite materials are manufactured as an additive process, in ply layers. The design of the plies affects how they are manufactured, and when compared to subtractive processes such as turning or milling, the constraints that the manufacturing process and the material behaviour place on the design are typically more restrictive, and complicated to apply.

Many of the articles found under this theme describe a process or a tool that either improves an existing design to suit a composite manufacturing process, or ensures the design can be manufactured from composites when it is created.

2.4.2 Review of DFM for composites

The research articles found under the theme of DFM for composites could all be differentiated by the stage in the design lifecycle where they are applied, and the type of problem that each article is attempting to address. Two distinct groups emerge; articles which describe methods that are applied after the design has been completed, in order to improve the design for production, and articles describing an integrated methodology which addresses manufacturing at the design stage.

Post-design methods: Many of the post-design methods found, rely on a suitably high fidelity design on which a manufacturing analysis can be based. These tools require the designer to invest time creating a high fidelity design, and then retrospectively correct the design to suit the manufacturing process, essentially re-designing for manufacture.

Three interesting articles described the analysis of fibre angles and steering for a design, requiring the design to have ply-by-ply definitions of fibre orientation. The manufacturing process can then be simulated and the comparison between the designed and manufactured fibre orientations can be compared [52]. The designer could also use the analysis to exploit steering to align to load paths to achieve a lower mass design [53], or a structurally stronger design [50].

The optimisation of the laminate stacking sequence, the sequence of ply orientations through the laminate, was described as a method to improve manufacturing cycle times in the resin transfer moulding (RTM) process [54]. This article described the use of a genetic algorithm to re-sequence the orientations of plies in a stacking sequence to suit a faster infusion time, albeit at the sacrifice of structural performance.

The majority of related research articles in this theme describe DFM being carried out through the use of manufacturing simulation once a design has been created. The required fidelity of the design varies across the articles.

By capturing the constraints of the manufacturing process in analysis software, a detailed design can be improved, and future similar designs can be constrained [55]. Using the RTM process as an example, the manufacturing process simulation can be used to generate a process performance index, which can be used to improve future designs [56]. Whereas these two articles both required a detailed design to carry out the analysis with, but with the results being applied to aid future designs, several articles described the use of existing designs to generate design constraints which ensure manufacturing knowledge is embedded during the design stages. One article describes the generation of a numerical representation of elements of the manufacturing process, which relate directly to design parameters [57]. This enabled a basic manufacturing analysis to be carried out on a preliminary design. Manufacturing cost estimation as also presented as a function of design variables in order to predict manufacturing cost at a design level [58]. Whilst both Boeing, with their PACKS system (Parametric Composite Knowledge System) [59], and Airbus, with their NGCW programme (Next Generation Composite Wing) [60], described a

parametric modelling approach to embedding manufacturing knowledge into design tools as a way to eliminate design features that might generate high manufacturing costs.

Design and manufacturing integrated methods: The integrated methods all enabled the manufacturing constraints to be considered by the design without the need for a design to be fully detailed first. The methods could be divided into three different classifications: Multi-objective design considering manufacturing optimisation, modifications to the design lifecycle, and process interaction and knowledge exchange.

The multi-objective design and manufacturing optimisation articles offered alternative exploitations of multi-objective optimisation tools:

- The use of a Nelder-Mead method of multi-objective optimisation, applied to a simultaneous structural and manufacturing optimisation problem [61], described the optimisation routine and the mathematics in great detail. However the chosen manufacturing objectives in the simultaneous optimisation are to minimise the angular difference between plies in the laminate. This objective reduces cure-distortion of the laminate but has negligible impact on production cost or cycle time.
- A simulation based performance assessment of the RTM process which calculates a performance index for the process was described [56]. The index was used as a design score and became an objective in a genetic algorithm based optimisation to help improve the design for the RTM process. A similar article describes a genetic algorithm applied to optimise the gate and vent locations in an RTM component design [62]. The article successfully demonstrated the advantages with reduced cycle times and lower defect count, however the structural performance of the component was not an optimisation objective. Alternatively, the design for manufacturing process flow applied to the problem of converting a uni-direction material design into a woven RTM design as a means to reduce production costs [63], enabled both the performance and the production of the design to be improved. A constraint satisfaction

problem solver was used to enable manufacturing constraints to be factored into the design optimisation process.

- The Integration of the manufacturing cost model into the structural optimisation process for a composite component, providing two conflicting objective functions – low cost and low mass was discussed. The multi-objective optimisation problem is built around these objectives using NSGA-II genetic algorithm [64], and a framework that includes a parametric CAD model of a wingbox, a cost estimation program and a finite element model integrated into a solution framework was used to validate the method.
- The reduction in uncertainty allows smaller safety factors to be used in a design and therefore results in a lighter, less conservative component, so the laminate ply thickness, ply orientation and fibre volume fractions can be evaluated with the aim of reducing their manufacturing uncertainty [65]. The reduction in uncertainty is achieved by coupling an optimisation system to a probabilistic analysis.

The majority of the integrated design and manufacturing articles were classified as modifications to the design lifecycle, with most of the research looking at replacing metallic designs with composites, or providing a general design improvement. These articles described the following methods:

- A mass transit application for replacing metal structures with rectangular, V and C section thermoplastic elements [66], including detailed analysis of the proposed manufacturing process and design/laminate down-selection [67].
- Replacement of skeletal metal frames and plywood panels in a mass transit application with a low cost fibre reinforced thermoplastic. Optimisation tools to evaluate structural performance enabled a 40% mass reduction [68].
- Lessons learned and existing cost engineering knowledge fed into each stage of the design life-cycle to aid in the reduction of cost by design [69].

- Discussion of the relationship between design performance and design parameters in a design system [70].

DFX terminology defined to include all 'design for x...' principles (like design for manufacture or design for reliability), however one article [71] proposes the use of a graph-theoretic approach to account for all DFX impacts for a selection of different design variables such as material type. This highlights the effect that the design decision has on different design-for variables, such as cost or mass. There were six other research articles that described a similar DFM principle, and these can briefly be summarised as:

- The replacement of a metallic aircraft floor beam with a thermoplastic composite beam by the application of design for manufacturing principles [72]. The other DFM research articles included:
- Design for manufacture process applied to a robotic arm use case in order to derive a DFM-algorithm [73].
- Design for manufacture evaluation of a helicopter tail boom manufactured using automated fibre placement rather than hand-laminating [74].
- Concurrent product definition and design for manufacture and assembly techniques applied to a wing-tip device to successfully reduce cost [75].
- Interaction between concept design and design for manufacture formulated and solved using the compromise decision support process [76], [77].

Research into the process interaction and knowledge exchange between the design and manufacturing stages of the design lifecycle all address general design improvements and component quality improvements. These include the use of a decision support problem approach to consider design, manufacture and maintenance concurrently in a domain independent tool [78]. And also the use of an integrated knowledge framework in order to provide quantitative manufacturing analysis of a composite design [79], focused on the detection and reduction of the formation of voids during the cure cycle.

Another article describes the use of statistical process control to identify and therefore reduce the risk associated with design decisions for the manufacture of a composite component [80]. Similarly, the introduction of a knowledge-based decision-tool into the design optimisation stage is described as a method to enable DFM to be adopted for a composite design [81].

These research articles can be tabulated in order to identify the type of method described, and whether it is applied pre or post design, against the type of problem the method aims to address. This is shown in Table 4.

Table 4: DFM for composites research classified by tool and problem

Problems Addressed	Methodology classification					
	Post-design analysis			Integrated into design		
	Fibre angle & steering	DFM by manufacturing simulation	Optimising laminate stacking sequences	Multi-objective optimisation	Design lifecycle improvement	Process interaction and knowledge exchange
Design/ Manufacturing variance	[52]					
Replace metallic design					[66] [67] [68] [72]	
Reduce mass	[53]	[57] [59]			[69]	
Reduce process time		[57]	[54]			
General design improvement	[50]	[55]		[61] [56] [63] [65]	[70] [71] [73] [74] [76] [77]	[77] [80] [81]
Improve component quality		[56]		[62]		[79]
Reduce manufacturing cost		[80] [58]		[64]	[75]	

2.5 Digital tools for DFM

In this section, the literature related to the digital tools used to support DFM is reviewed. Whilst the research related to composite design, composite manufacturing and DFM discuss problems, methods, theories and use cases, this section describes research that is orientated around specific digital tools that are used to support DFM. Industrially designed and manufactured composite components are reliant on robust digital tools that can be reliably integrated together across the whole design lifecycle.

Background on digital tools for DFM: This theme includes research articles that describe a digital tool that can be used to support design for manufacture. Two broad classifications can be used to define the results, with the tool being classified as either composite manufacturing specific or non-composite manufacturing specific.

Review of digital tools for DFM, non-composite manufacturing: Some of the tools described in research that address DFM methodology, but did not focus specifically on the composite manufacturing constraints. These tools can be grouped into three distinct categories: Theoretical modelling, manufacturing knowledge capture and process simulation.

Four research articles that address theoretical modelling took the approach of building a physics-based model of machine and material characteristics in order to predict performance and quality [45], and using 2D to 3D model transformations for fabrics (garment industry not aerospace) using a spring/mass model [82]. Alternatively, the use of a physics-based theoretical model could be used to predict crash performance in a composite structure in order to reduce the degree of physical testing required [83], and research using the semi-empirical approach to modelling the unknown or unaccounted composite design parameters that are often ignored by metal-biased design tools [84].

The research focusing on capturing manufacturing knowledge addressed different areas of the design lifecycle. In terms of conceptual design and design

configuration, the modelling of a decision support problem influencing design, manufacture and maintenance requirements by described as creating a domain independent system [76] [77] [78]. Another concept design tool described the parametrisation of conceptual design variables to allow manufacturing time and cost to be evaluated for re-design as well as design scenarios [85].

At a detail design stage, the use of a materials database was proposed to define manufacturing and design performance of materials during the design phase [15]. Looking at knowledge based engineering, KBE, an article provided a review of engineering KBE research to help identify the industrial KBE requirements and opportunities [86].

Several simulation tools were described in literature. The simulation of dry fibre placement technology, infusion and cure processes was described as a method to develop knowledge and parameter interactions [87], the digital tool used generated a lower cost structurally optimised design. In a more performance-based simulation, the analysis tool LS-DYNA was used to model crash performance of composite structures [88].

Looking at the manufacturing stage of the design lifecycle, one article described the simulation of laminate quality with links to non-destructive testing in order to capture more accurate manufacturing costs [89] at a detailed design stage.

Review of digital tools for DFM, composite manufacturing: Some of the research articles related to digital tools for DFM describe tools or methodology focused on features that are composite manufacturing specific, such as fibre trajectories and fibre angular deviation due to fabric draping. The research can be categorised as either fibre-path optimisation or draping simulation:

The fibre-path optimisation research utilised three different approaches. Two articles featured optimisation, surrogate modelling with NSGA-II genetic algorithm to optimise curvilinear fibre paths for buckling and stiffness [90], and optimisation and evaluation of lamination parameters against the variable stiffness parameters or a composite panel design [91]. One tool described was used to assist the designer improve the generation of fibre paths by developing

a streamline analogy to optimise tape course seed points and trajectories, with the benefits of maximising smoothness and minimising thickness variations [49].

The research related to draping simulation feature the use of a simulation tool that is able to analyse a design and predict the fibre angle changes in the composite material after it has been draped into a 3D shape. The first article describes a two stage approach to simulate fabric draping with an FE tool and then perform a manufacturing cost/structural weight optimisation to achieve a higher quality draped component (C-Shaped spar) [44]. The use of kinematic modelling of composite materials was also proposed as a method to improve the potential of hand lay-up processes [92].

Draping simulation was also used in conjunction with mathematical modelling of the subsequent consolidation of the laminate. This toolset aimed to improve structural performance of a composite laminate [47]. Lastly, a numerical draping simulation was used to adapt 1980's clothing industry technology to modern automated composite manufacture where dry fabric is cut and positioned similarly to automated clothing manufacture [84].

The digital tools described in this section are represented in Table 5, highlighting the tool method described and the objective of the tools function.

Table 5: Digital tools for DFM classified by tool method and tool objective

Tool objective	Tool method				
	Design focused			Manufacturing focused	
	Theoretical modelling	Knowledge capture	Process simulation	Fibre path optimisation	Draping simulation
Improve structural performance				[49] [90] [91]	[47]
Reduce manufacturing cost		[85] [86]	[89]		[44] [84]
Manufacturing process improvement	[45] [82]	[78] [76]			[92]
Reduced component mass		[77]			
General design improvement	[83] [93]	[15]	[87] [88]	[94]	

2.6 Systematic design processes

When the literature published in the field of DFM for composites is evaluated in the context of the overall design processes, there is an absence of information regarding the design processes followed. In one review paper [95], as the design fidelity increases, the manufacturing complexity also increases at the detriment of production speeds. The paper also highlights that up to 80% of the manufacturing cost is committed by the decisions made at the conceptual design stage. Work carried out by G Gonzalez [96] evaluated the state of the art for design for manufacture of curvilinear fibre path laminates highlighted that the design rules did not transcend from design concept to sufficient detail to manufacture a laminate. This highlights the need for the higher fidelity design

rules around detail designing advanced laminate structures enabling them to progress through the design lifecycle to physical manufacture.

At the NCC there is research being carried out in order to capture AFP design rules and manufacture a series of demonstration components that exploit curvilinear fibre paths, including an objective to record the design for manufacturing requirements as the design evolves.

Very few relevant articles were found relating to the methodology of evaluating conflicts between composite manufacturing constraints and detail design requirements, but a number of relevant articles have been published which describe the way that the functionality or aesthetics of the end product can be affected and therefore taken into account by upstream design decisions. The most relevant article looks at the aesthetic and perceived defects in a product which are often subjectively measured by the end user, and uses a Failure Modes and Effects Analysis approach to suggest changes in the conceptual design stage of a product [97]. The article is relevant to this research as it tackles the challenge of the effect of a design decision being difficult to measure. In the article the effect is difficult to measure because the analysis is subjectively carried out by the unknown end-user, and in the composites application, the effect is difficult to measure due to the lack of historic experience gained and documented when manufacturing novel designs. Another relevant paper also suggests process FMEA as a sensible methodology to evaluate a concept design. The use of functional design analysis diagrams in conjunction with FMEA is suggested by Michalakoudis et al [98] as a way to augment the FMEA process with visual representations of the key detrimental interfaces in a design. This approach can be applied to the case of composite manufacturing constraints applied to the detailed design stages, highlighting when design improvements are likely to have a negative impact on the corresponding manufacturing process steps.

2.7 Key trends and research gap

This section describes the trends that can be seen in the published literature, and discusses how they contribute towards the definition and validation of the research gap. In order to make sure that meaningful research was found, and ensure relevance to the research theme, a structured search approach was used. This started with the research scope, and progressed through to the identification of research trends and the research gap analysis (presented in sub-sections 2.7.2 and 2.7.3 respectively). Finally, a discussion of the findings obtained from the literature survey is presented in sub-section 2.8.

2.7.1 Discussion and Assessment

This section describes how two different approaches were used to assess the research articles discussed in the literature survey. Firstly, the author provided initial screening, acting as a subject-matter expert for DFM of composite structures. This is based on the authors 13 years of experience working in the aerospace industry, working on projects addressing the introduction and industrialisation of composites for primary aircraft structures. This experience ranges from the development of automated production methods for the Airbus A350 wing, with several patents awarded for new technologies, through to the multi-disciplinary design optimisation of a composite wing, intended to replace a current single-aisle metallic aircraft.

In order to assess research articles that fell outside of the authors' expertise, a wider group of experts was required. This formed the second assessment technique. A series of individual discussions were held with other experts located in industry and academia to establish a better understanding of the state of the art, and to enable the identification of research gaps arising from the literature analysis. The group of experts is described in Table 6. The questions the experts were asked is described in Table 7.

Table 6: Description of expert support

Expert ID	Area of expertise	Location	Field	Years of experience
Expert 1	KBE systems supporting DFM and manufacturing	Industry	KBE + DFM	17
Expert 2	Digitisation and optimisation of manufacturing processes	Academia	MDO + KBE + Optimisation	13
Expert 3	Manufacturing informatics and engineering optimisation	Academia	MDO + KBE + Optimisation	17
Expert 4	CAD application development and aerospace optimisation	Industry	Design + MDO	13

Table 7: Expert questions

Ref	Questions
1	How is the article relevant to DFM for automated composite manufacture?
2	Does the article lend itself to industrialisation?
3	How credible is the article content?
4	What is the novel aspect to the research in the article?

2.7.2 Key trends

This section describes the assessment of the literature surveyed in sections 2.3, 2.4 & 2.5, and identifies the key trends that emerge when the research articles are grouped together and classified.

Design and manufacture of composites: The 25 research articles reviewed in this section fell into two fundamental groups, with 13 articles describing an improvement to a composite design, and 12 articles describing a composite manufacturing improvement. The classification of these articles is illustrated in Table 3. The majority of the design improvement articles described a design improvement achieved by design optimisation, whereas the manufacturing improvements were divided between improvements to the design and reduction of component cost. The key trend observed is that design improvement research is dominated by performance optimisation methods, and manufacturing improvement research is dominated by process simulation methods. This can be seen in Table 3.

DFM for composite structures: The 32 research articles reviewed in this section fall into two groups: 10 articles that required a detailed design before any manufacturing analysis could be carried out, and 22 articles that integrate the manufacturing constraints into the stage where the design is created.

The articles can be re-categorised to identify which stages of the design lifecycle they address. This is shown in Table 8.

Table 8: DFM articles and the span of the design lifecycle they address. Colour coded red for single stage, through to dark green for full lifecycle.

ID	Design Lifecycle					
	Concept Design	Preliminary Design	Structural Definition	Detail Design	Manufacturing Design	Physical Manufacture
[52]	<div>Colour Key</div> <div>1 Stage</div> <div>2</div> <div>3</div> <div>4</div> <div>5</div> <div>6 Stages</div>					
[67]						
[54]						
[68]						
[69]						
[61]						
[70]						
[71]						
[55]						
[57]						
[78]						
[72]						
[56]						
[59]						
[62]						
[53]						
[79]						
[63]						
[73]						
[64]						
[74]						
[75]						
[60]						
[80]						
[81]						
[65]						
[58]						
[76]						
[77]						
[50]						
[95]						

The key trend identified in Table 8 is that few of the articles address the full design lifecycle and validate their proposals by manufacturing trial. Only one of the articles addresses all stages of the design lifecycle, taking a conceptual design through to a physical component [95]. Furthermore, only three of the articles start with a concept design and develop it as far as a manufacturing ready design, but these articles did not validate by physical trials. Several articles did manufacture physical trials to validate their claims, but they all started with designs that had a medium or high level of fidelity. The majority of the articles only addressed a narrow section of the design lifecycle. Table 8 is colour coded based on how far across the design lifecycle the research spans, with dark green spanning all stages of the design lifecycle and the colours transitioning to red where the research only covers a single stage of the design lifecycle.

Digital tools for DFM: The 21 research articles describing digital tools for DFM were split between 13 articles focusing on the design and 8 articles focusing on manufacturing. Table 9 lists the articles and the software they describe, plus the method used to verify the research. Only 7 of the articles verified the methodologies proposed by physically manufacturing a composite demonstrator. Many of the other articles describe a method and digital tool that enables manufacturing knowledge to be integrated into the design to enable manufacture, but they do not manufacture the design.

Table 9: Digital tools for DFM research, software described and validation method

Article	Methodology	Software	Verification
[90]	Yes	Matlab	Theoretical
[49]	Yes	Matlab	Theoretical
[44]	Yes	SEER MFG & ABAQUS	Curved C-Spar
[45]	Yes		
[92]	Yes	MSC	Theoretical
[47]	Yes		
[82]	Yes		
[76]	Yes	DSIDES & WIND	Theoretical
[77]	Yes	DSIDES & WIND	Theoretical
[78]	Yes	DSIDES, WIND & INWIND	Theoretical
[85]	Yes	CLIPS	Metallic Flange
[15]	Yes	Composite Star	
[91]	Yes	Matlab	Composite Flat Plate
[87]	Yes	CADFiber & CATFiber	Composite Panel
[83]	Yes	ABAQUS	Corrugated Composite
[88]	Yes	LS-Dyna	Composite Cone
[84]	Yes		
[89]	Yes	SEER MFG & ABAQUS	Composite Cover
[93]	Yes	Fortran	Theoretical
[94]	Yes	AR Toolkit	VR Modelling
[86]	Yes		
[95]	Yes	ACES, CATIA, CADFiber	Composite Panels

Design processes: No literature was found to address the topic of taking a systematic approach to applying manufacturing constraints to a design. As highlighted in the work of G Gonzalez [96], the methods of improving the performance of a structure at the concept design stage is well researched and documented, but there is little knowledge published to enable higher fidelity design of advanced laminates when it comes to manufacturing them. At the NCC a number of projects have been designed and manufactured using fibre placement technology which needed significant design evolution from the initial design to the point where they could be successfully manufactured, however the methodology for applying these design changes has not been recorded or published, and each designer employs an individual approach. The relevant research that evaluates other de-risking of downstream design and manufacturing activities has not yet been applied to a composite laminate design use-case.

2.7.3 Gap analysis

The trends in the composites literature suggest a research gap in three areas; a lack of manufacturing constraints being addressed in the early stages of the design lifecycle, a shortage of research verified with physical use cases, and the need for methods to design for automated production techniques.

The absence of research articles that address manufacturing constraints in the early stages of the design lifecycle can be seen in Table 8, but when combined with the information shown in Table 9, it can be seen that few research methods exist for a full lifecycle DFM approach. The gap led the author to conclude that there is the lack of a design process and relevant strategies to use digital technologies to facilitate design for automated manufacture for composite structures.

Many of the tools and methods described in the surveyed literature differ from the tools and methods used in the composites manufacturing industry, and the assembled research did not adequately describe a DFM method or strategy with equivalent fidelity to the current industrial practices, and only two of the research articles used relevant industrial use cases. This led to the creation of the

research objective “Capture the current industrial design practices using use cases for composite structures.”

The research summarised in Table 8 and Table 9 illustrate a lack of published material both validated by physical trials, and also describing how to best design for industrial scale automation systems that aren’t readily available to academia. As an example, the majority of articles that describe a fibre steering methodology rely on the Matlab digital toolset, however it is common that industrial fibre placement machines are programmed using CAD data as a geometry source, and none of the articles described a method for converting and using the Matlab data in a digital CAD toolset. This led to the creation of the research objective “Develop strategies for applying DFM best practice through the use of digital tools.”

A number of the research articles described digital tools which are difficult to integrate into industrial machinery. For example, several articles described the use of Matlab to generate design data, however importing the geometry from Matlab into CAD or machine programming software is complex, and requires the data to be translated into a format that is supported by these industrial software packages.

The DFM research reviewed was not specifically targeted at automated composite deposition processes, and only two articles specifically described research focused on designing for an automated manufacturing process. These articles described a greater number of manufacturing constraints over the conventional composite material constraints which highlights that DFM for automated production of composites is likely to be more complicated than DFM for composite materials. This led to the creation of the research objective “Develop a design process and supporting tools to systematically apply DFM for automated composite manufacture.”

This analysis led the author to define the hypothesis that it is possible to have a generic design process to support the design for automated manufacturing of composites components.

2.8 Concluding remarks

The analysis of existing literature provided a basis on which the research background could be established, and enabled the identification of meaningful research trends. The research trends helped to validate the research gap, and position this research and its contribution to knowledge.

The research gaps are summarised in Table 10 showing the gap identified, along with the corresponding illustrations and data.

Table 10: Research gap and supporting data

Objective	Research Gap	Related Material
1 – Capture the state of the art for DFM of composites using digital technologies	The lack of manufacturing constraints being addressed in the early stages of the design lifecycle	Section 2.7.2, Table 8, Table 9
2 – Capture the current industrial design practices using use cases for composite structures	A shortage of research verified with physical use cases	Section 2.4, Section 2.5, Table 4, Table 5, Table 8, Table 9
4 – Develop a generic process and supporting tools to systematically apply DFM for automated composite manufacture	The need for methods to design for automated production techniques	Section 2.5, Table 4, Table 5, Table 9

The evaluation of the research trends and research gaps led to the conclusion that there is a need to develop and publish a design process and relevant strategies to enable the use of digital technologies to facilitate design for automated manufacture for composite structures. Many of the digital tools identified support a generic subtractive design process, while the composites

manufacturing process is better supported by an additive approach. The additive approach to DFM was not found in the surveyed literature. This research gap represents an opportunity to validate the research hypothesis.

Three key conclusions have been drawn from the work described in this chapter:

- Composite structures are manufactured using complex processes, some of which are automated on an industrial scale. These manufacturing processes require specific considerations to be taken into account at all stages of their design lifecycle, yet the processes and tools used during the design do not always account for these considerations, resulting in the creation of sub-optimal designs.
- The design lifecycle increases with fidelity from concept through to manufacture, however many existing tools can only evaluate manufacturability from high fidelity design data, so there are opportunities to find ways to evaluate manufacturability using lower fidelity design data and therefore integrate with earlier stages of the design lifecycle.
- In order to integrate the design for manufacturing approach into the design stages, the composite manufacturing constraints associated with the manufacturing process need to be identified at the beginning of the design lifecycle, this implies that the manufacturing process is identified, and the process constraints are known. There is an opportunity to develop a systematic methodology to identify and then account for manufacturing constraints when the manufacturing process is novel or has low maturity.

The research aim and objectives described in section 1.3 have been derived from the research gaps identified in this chapter, and they encompass the three challenges described in this section. Whilst the surveyed literature has supported the development of the research aims and objectives, the next chapter will address the missing industrial practice needed to further validate the research hypothesis. This is done by analysing the design practices for composite structures in the context of design and manufacturing in the aerospace industry.

3 CAPTURING CURRENT PRACTICES USING INDUSTRIAL USE CASES

The purpose of this chapter is to present industrial research related to the research topic. The industrial studies aim to identify engineering methodologies which describe the practice used to design composite structures. The studies were all undertaken by the author whilst working in the aerospace industry, and are deemed relevant to this PhD thesis on the basis that they address the different stages of the design lifecycle identified as potential gaps in the literature survey.

The examples described in this section are taken from the aerospace industry, and focus on two different aircraft programmes, one moving from concept to preliminary design and then detailed design, and the second, from preliminary design into detailed design and then production. The two programmes are therefore able to represent the development of a composite aircraft structure through the entire design lifecycle.

3.1 Introduction

The industrial best practice can be split into four discrete themes, which align to the initial stages of the composite structure design lifecycle. The design starts its life with very low fidelity as a concept, which fundamentally sets out the layout of the structure and makes initial technology and material selections. An example of the distribution of material selected for a concept aircraft are illustrated in Figure 8.

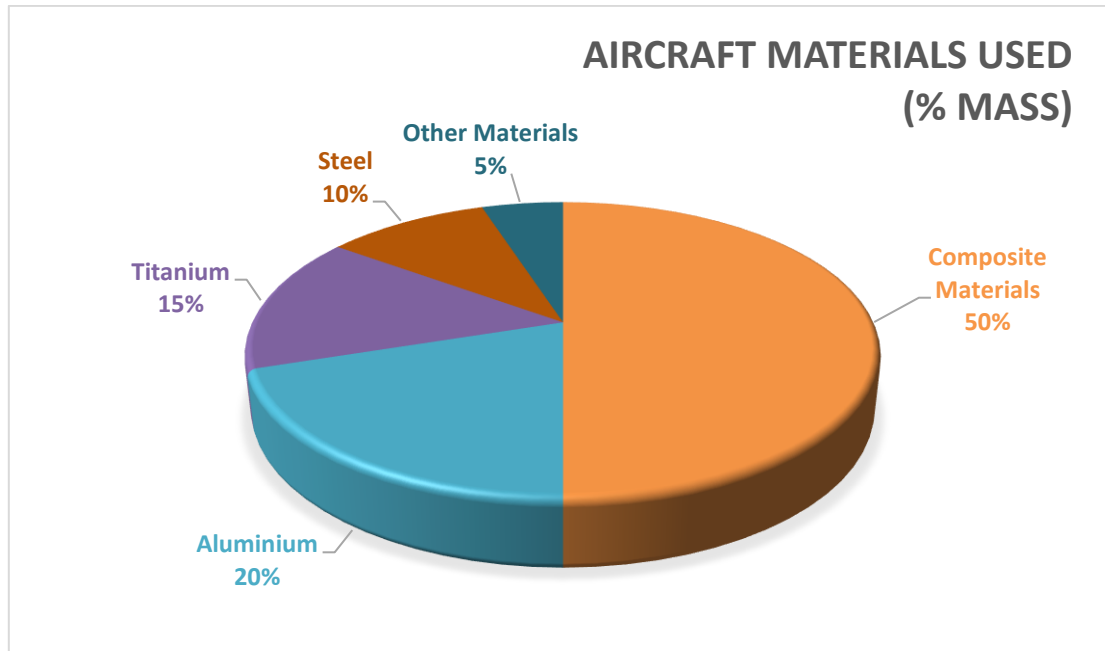


Figure 8: Material selections on an early concept aircraft, percentage of total airframe mass

The preliminary design stage increases the concept design fidelity and maturity to a point where an evaluation of the design can be made. It is at this point that Airbus perform trade studies comparing multiple preliminary designs to select the most suitable before progressing to the next stage of the lifecycle [99]. Once the preliminary design is completed, a detailed design is used to further increase design fidelity and maturity to the point where a physical part can be manufactured. In the manufacturing stage, process improvements and manufacturing lessons learned can be identified and fed back into the detail design to further improve it.

3.1.1 Conceptual Design

The conceptual design stage of the design lifecycle for an aircraft describes the overall aircraft definition. In this stage the fundamental layout of the aircraft is considered, such as the main geometry of the wing and location of landing gear and engines. The concept stage concludes when a set of 3D surfaces that define the 'skin' of the aircraft have been defined.

The design fidelity at this stage is very low, which makes it difficult to utilise many of the manufacturing analysis tools which require a much higher design fidelity to function.

The concept design is typically only used to establish a flight performance envelope as part of a multi-disciplinary assessment against the aircraft top level performance objectives. At this stage in the design it is not considered practical to evaluate manufacturing due to the low maturity of the data.

3.1.2 Preliminary Design

During the preliminary design of the aircraft, the initial surfaces generated at the concept design stage are structurally sized to suit the load cases from the multi-disciplinary assessment. It is typical that several worst-case flight manoeuvres are simulated to generate the maximum load cases that an aircraft structure will experience during flight, and these loads are calculated with a conservatively thick structure, defined as a thickness at each node in the loads finite element model (FEM). The FEM model is analysed for flight loads, and material is removed from areas with excessive stiffness or strength, before re-iterating the loads analysis. The loads analysis and adaption of the structural thickness definitions are re-iterated until the performance and structural definition converge. The preliminary design concludes when the structural definition optimisation converges and the 3D surfaces are accompanied by detailed sizing data.

The process of optimising the structure is very similar to the subtractive process of machining a metal billet into a final shape, starting with a thickness of material that is larger than the finished component, and systematically removing material where it is not required for structural performance. The process focuses on discrete cells which are processed individually not globally.

3.1.3 Detailed Design

The preliminary design consists of only 3D surfaces and material thickness definitions, but these need to be converted to a 3D solid model with laminate definitions. The detailed design process is used to systematically convert the

3D surfaces into a series of 3D ply layers based on the material thickness data. These 3D ply layers are then built up into a 3D solid model of the composite structure, but with a layer-by-layer definition of each composite ply shape, boundary and fibre direction.

The process of constructing the detailed laminate design is an additive process, and is globally addressed rather than focusing on individual cells in the structure.

Once the detailed laminate design is completed, the laminate stacking sequences are checked for compliance with manufacturing constraints and design rules, and then the ply shapes are checked to see if they are compatible with the manufacturing process.

Each individual ply shape and surface is defined at this design stage, but the real life direction of the fibres is not established. Each ply only has a target fibre orientation set.

3.1.4 Manufacture

The detailed design does not have sufficient maturity to be used to create a manufacturing machine program from. So in the manufacturing stage, each ply is taken from the detailed design, and the fibre trajectories are generated based on the target ply orientation specified in the design. In this operation, the geometry of the surfaces causes the fibres to follow non-linear trajectories, so the manufactured fibre angles for each ply are represented as a maximum and minimum deviated angle.

3.2 Methods followed to evaluate best practice

The literature survey described a number of different methodologies to carry out design activities on composite structures, but these do not correlate with the routine way in which composite structures are developed in the aerospace industry. The author was involved in a series of Airbus composite structure development programmes as an employee of Airbus, and of the National Composites Centre, and this experience gathered over 13 years has enabled

the recording of industrial best practice. The Airbus projects which enable the author to identify best practice are the MDOW programme [11] and the NGCW programme [10], where the author was responsible for defining how manufacturing would be represented in the process for selecting aircraft concepts, and for detail designing a composite wingbox structure respectively. Prior to this, the author was responsible for introducing the AFP process to Airbus UK as part of the development of the A350 aircraft. The NCC project which enables the author to identify best practice is the 3 year long Dry Fibre AFP core programme, led by the author on behalf of the NCC tier 1 members. Each programme was concluded with a lessons learned exercise which identified any new best practice that was created, and the extracted best practice was only disseminated amongst the programme participants. The information described in section 3.3 is based on use cases which enable the best practice to be described with the added context of the industrial application. The case studies are validated with worked examples and trial data to demonstrate a successful conclusion.

3.3 Examples of DFM for composites in the aerospace industry

The following three industrial use cases highlight typical design challenges and methodologies common in the aerospace industry, enabling the reader to understand the context of designing for composite manufacture in the aerospace industry. These use cases were selected from previous research programmes that had generated new industrial practices relating to these topics.

3.3.1 Industrial case 1: Sizing a composite structure

A preliminary design containing aerodynamic surfaces will undergo a structural sizing process, where the surfaces are given material thickness values that enable a structural analysis and optimisation based on flight loads to be performed. The process flow is illustrated in Figure 9.

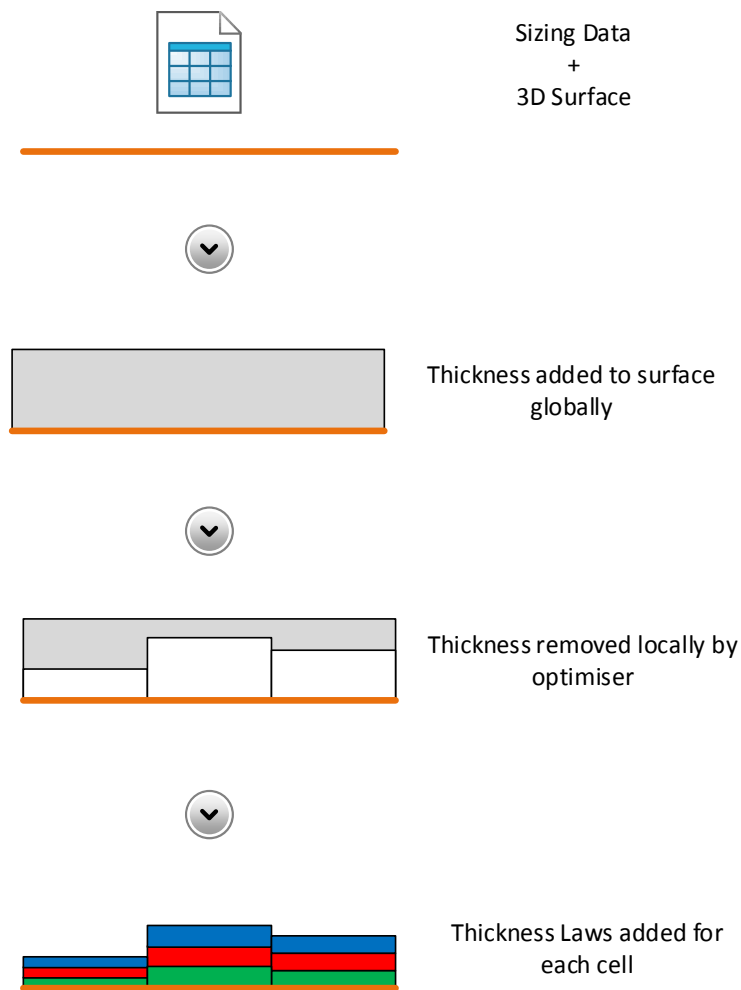


Figure 9: Schematic of preliminary design sizing process flow

For an aircraft wing, which is historically manufactured from metal, a subtractive sizing process is used. This process divides the wing surface into a grid of cells, split by the stiffening stringers and ribs. A maximum material thickness is applied globally to the wing, and an optimisation tool is used to systematically reduce the thickness in each cell until the minimum material required to satisfy the load cases is left. This subtractive process of sizing replicates the subtractive process of metal machining, resulting in a preliminary design which does not significantly increase in mass when the manufacturing constraints of machining are applied.

The change to composite materials from metals results in the structure being manufactured using an additive manufacturing process, where material is added in finite thickness ply layers, with a much larger quantity of manufacturing

constraints affecting the design. The risk associated with using the traditional subtractive sizing process is that the preliminary design that is generated does not accurately reflect the manufacturing process, and does not adequately address the manufacturing constraints. This can result in mass being added to the structure after the structural sizing optimisation stage has concluded, and the mass added later in the design lifecycle, post optimisation, creates a sub-optimal design.

The table shown in Figure 10 is a sample sizing table for an aircraft wing. The vertical cell boundaries represent the wing ribs, and the horizontal cell boundaries represent the stiffening stringers. The cell values represent the material thicknesses. A metallic design only requires a single table of material thicknesses, but a composite design requires the thicknesses and a second table with the same format containing cells that represent the composite thickness laws that match the corresponding thicknesses. A thickness law contains the percentages of each different fibre orientation by thickness. For example, a thickness law of 40/50/10 for a 10mm thick cell refers to the laminate in that area consisting of 4mm of 0 degree plies, 5mm of equally paired 45 and 135 degree plies, and 1mm of 90 degree plies.

Min Stress Thickness	Version 11	V1	V2	V3	V4	V5	V6	V7	V8	V9	V10	V11	V12	V13	V14	V15	V16	V17	V18	V19	V20	V21	V22	V23	V24	V25	V26	V27	V28	V29	V30	V31	V32	V33	
	H1					9.4	10.11	10.11																											
	H2	9.16	8.85	8.85	13.77	9.4	9.4	9.4	13.72	29.82	29.82	16.72	9.4	9.4	9.4	9.4																			
	H3	9.16	8.85	8.85	8.85	9.4	9.4	9.4	13.72	29.82	29.82	16.72	9.4	9.4	9.4	9.4	9.4	9.4	9.4																
	H4	9.16	8.85	8.85	8.85	9.4	9.4	9.4	13.72	29.82	29.82	16.72	9.4	9.4	9.4	9.4	9.4	9.4	9.4	9.4	9.4	9.4	9.4												
	H5	9.16	8.85	11.12	11.12	11.12	13.25	13.25	13.72	13.72	13.72	13.72	13.72	13.72	13.72	12.19	12.19	12.19	12.19	12.19	12.19	12.19	12.19	12.19	13.33	13.33	13.33	13.33							
	H6	9.16	8.85	15.24	15.24	15.24	15.24	15.24	15.24	15.24	15.24	15.24	15.24	15.24	15.24	15.24	15.24	15.24	15.24	15.24	15.24	15.24	15.24	15.24	15.24	15.24	15.24	17.32	16.44	13.71	13.71	11.42	11.42	11.42	
	H7	9.16	8.85	15.24	15.24	15.24	15.24	15.24	15.24	15.24	15.24	15.24	15.24	15.24	15.24	15.24	15.24	15.24	15.24	15.24	15.24	15.24	15.24	15.24	15.24	15.24	15.24	17.32	16.44	13.71	13.71	11.42	11.42	11.42	
	H8	9.66	8.85	11.12	11.12	11.12	13.25	13.25	12.68	12.19	12.19	12.19	12.19	12.19	12.19	12.19	12.19	12.19	12.19	12.19	12.19	13.33	13.33	13.33	13.33										
	H9	9.93	8.85	8.85	8.54	8.54	8.54	8.54	8.54	8.54	8.54	8.54	8.54	8.54	8.54	8.54	9.17	9.17	9.17	9.17	9.17	13.33	13.33												
	H10	9.93	8.85	8.85	8.54	8.54	8.54	8.54	8.54	8.54	8.54	8.54	8.54	8.54	8.54	8.54	9.17	9.17	11.87	11.87	13.33														
	H11	10.11	8.85	8.85	8.54	8.54	8.54	8.54	8.54	8.54	8.54	8.54	8.54	8.54	8.54	8.54	9.17	11.87																	
	H12	11.12	8.85	8.85	8.54	8.54	8.54	8.54	8.54	8.54	8.54	8.54	8.54	8.54	8.54	11.87	11.87																		
	H13	11.12	8.85	8.85	8.54	8.54	8.54	8.54	8.54	8.54	8.54	11.87	11.87	11.87																					
	H14	11.12	11.12	8.85	8.54	8.54	8.54	8.54	8.54	11.87	11.87																								
	H15	13.77	13.77	8.85	8.54	8.54	8.54	11.87	11.87																										
	H16	14.72	14.72	11.12	12.29	12.29																													
	H17	20.32	20.32	16.58																															

Figure 10: A sample wing sizing table (fishtail plot), with colour coded sample section highlighted in red. Each cell identifies the minimum thickness of material required in mm.

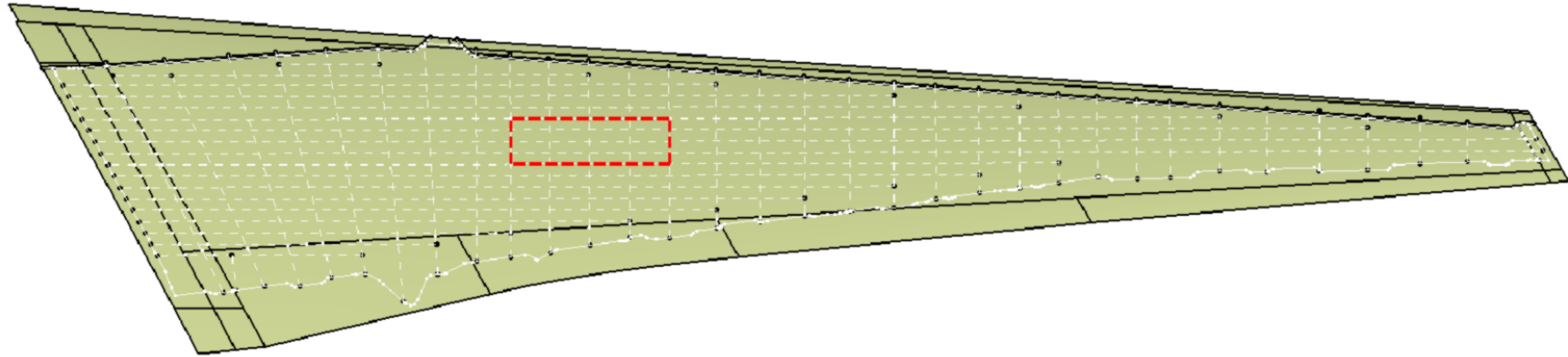


Figure 11: A 3D CAD representation corresponding to the wing sizing table in Figure 10, the area highlighten in red represents the sample illustrated in Figure 12.

The wing structural sizing data can be transposed onto a 3D CAD model, shown in Figure 11. There are two adjacent cells in this design which are identified as having the same thickness, but different thickness laws. These are highlighted in Red in both Figure 10 and Figure 11. Both adjacent cells require a thickness of 15.24mm, however the thickness law changes from 50/40/10 to 43/47/10 due to a local change in load-case. To simplify the example, 16 of the cells from the use case are shown as a uniform representation in Figure 12.

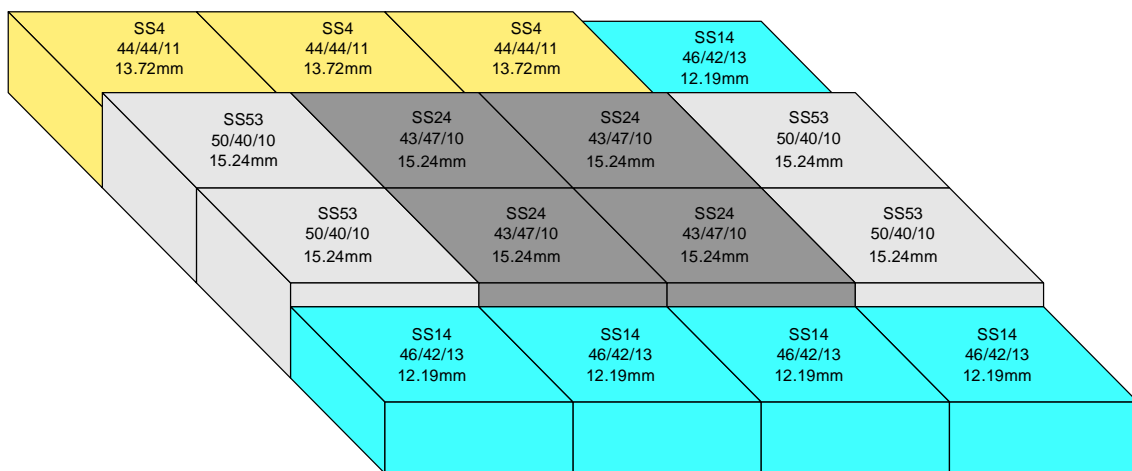


Figure 12: A simplified visualisation of part of the wing sizing data

The first stacking sequence is referenced as SS24 it consists of 43% 0 Degree / 23.5% 45 Degree / 23.5% 135 Degree / 10% 90 Degree, which is represented as a '43/47/10 thickness law' due to the balancing of the 45 and 135 plies. The second stacking sequence is SS53, which has a thickness law of 50/40/10.

SS24 has a sequence of:

(45/-45/0/90/0/-45/45/0/0/0/90/0/-45/45/0/0/-45/45/0/-45/45/0/45/-45/0/0/90/-45/45/0)S

SS53 has a sequence of:

(45/-45/0/0/45/-45/0/0/0/90/0/0/45/-45/0/0/90/0/0/-45/45/0/-45/45/0/0/90/45/-45/0)S

The S at the end of the sequence indicates that the sequence must be mirrored.

The order of the different ply orientations must be sequenced according to specific design rules to create a stacking sequence. The stacking sequences for the two cells is visualised in the cross-sectional representation of Figure 13.

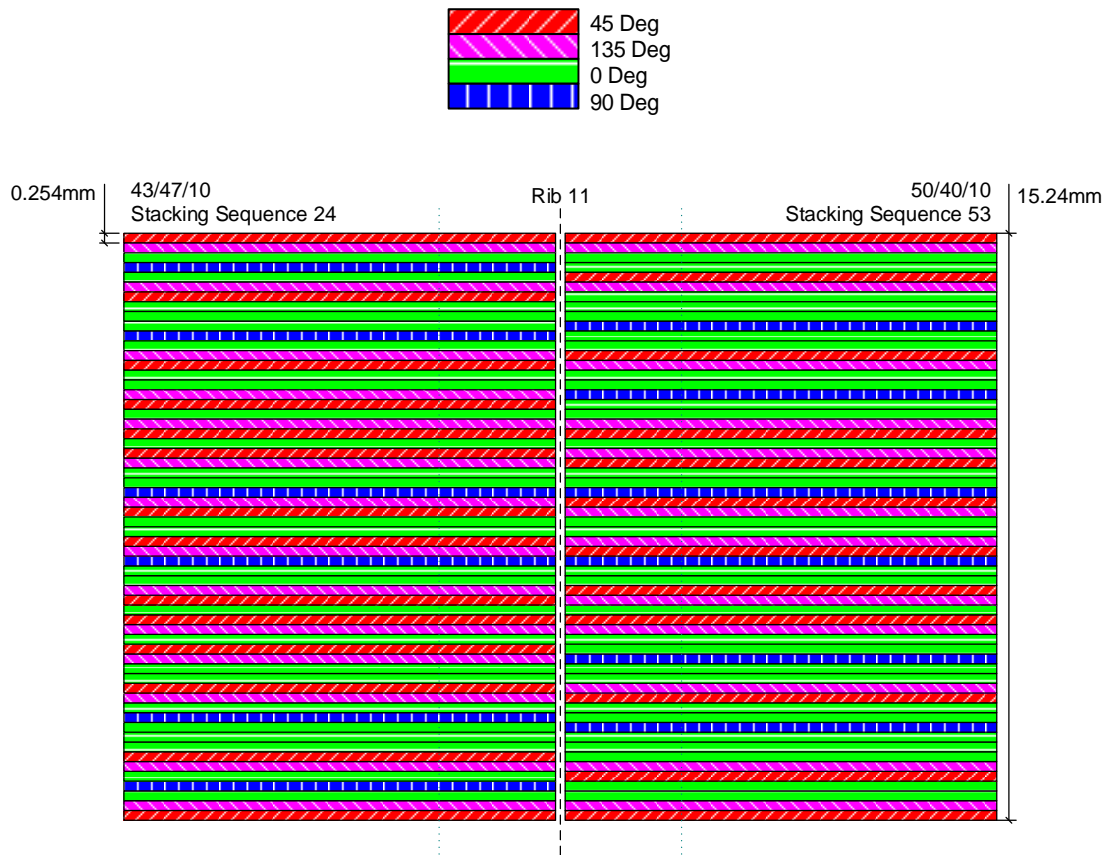


Figure 13: Representation of SS24 and SS53 as neighbouring stacking sequences

The different ply orientations in Figure 13 are colour coded, Green for 0, Red for 45, Pink for 135 and blue for 90. Each ply thickness is 0.254mm thick, but only 43 of the 60 plies are continuous from one cell to the next, so the 17 discontinuous plies must be overlapped to ensure that load is transferred from cell to cell efficiently. The resulting laminate gains a raised increase in thickness at the cell boundary, which is shown in Figure 14 as an increase in thickness from 15.24mm to 18.796mm.

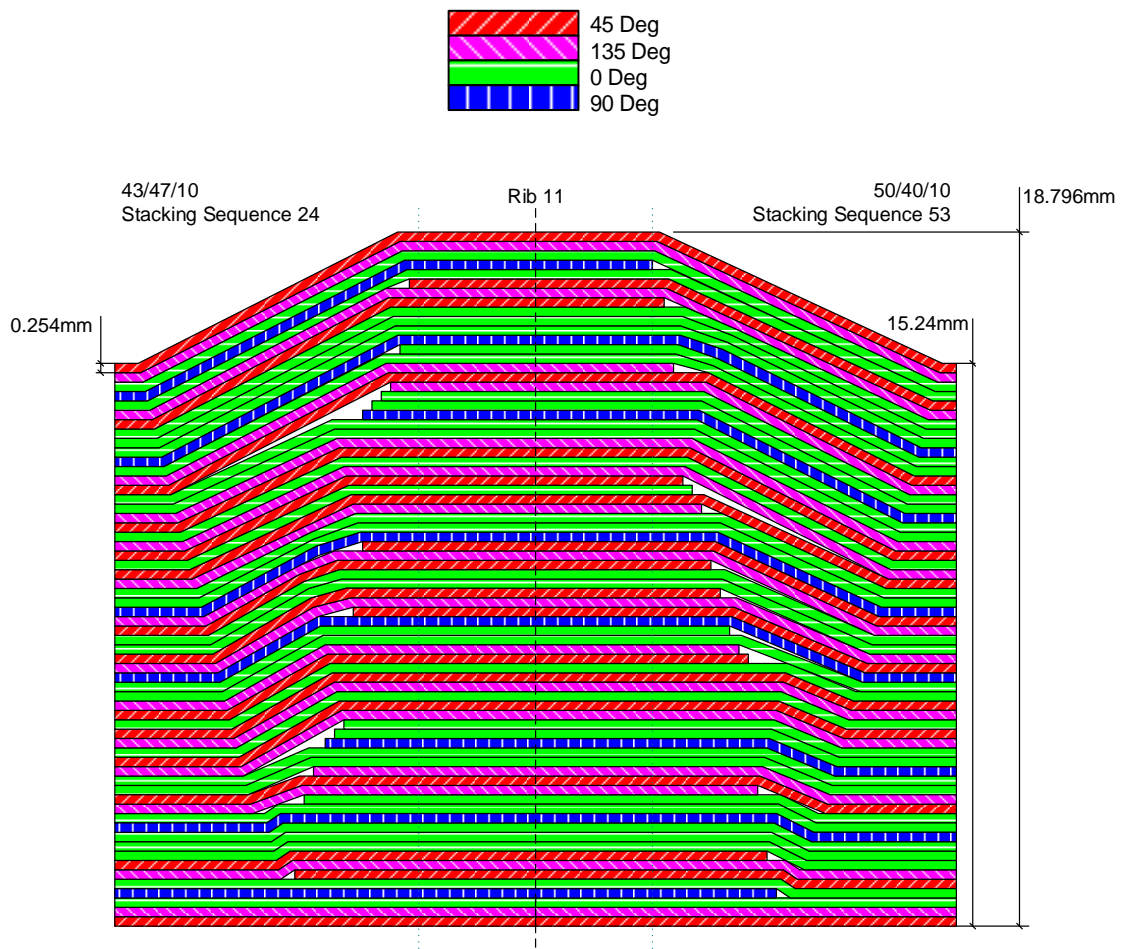


Figure 14: Representation of how SS24 and SS53 merge to create an overlap

The requirement to achieve same-orientation ply continuity between neighbouring cells is a manufacturing constraint which is not represented during the structural sizing process. By not accounting for the constraint when the cells are sized individually, the design solution gains mass during detailed design, after the structural optimisation has completed, resulting in sub-optimal mass being added. Figure 15 illustrates the 3D representation that was used for structural optimisation (on the left), and the post-detail design 3D representation (on the right) with all the additional material added highlighted in red.

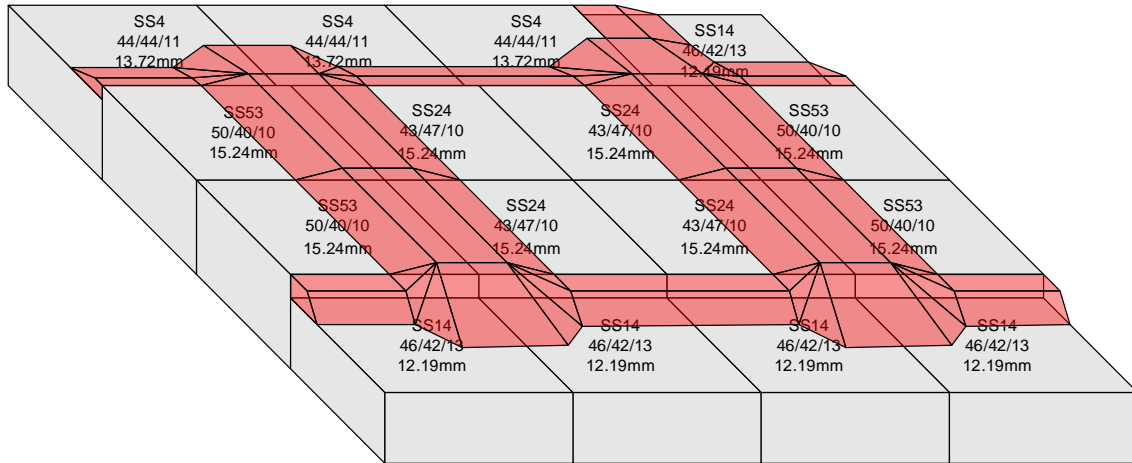


Figure 15: Visualisation of additional mass added due to mismatched thickness laws

Prior to this example, structural sizing processes did not take into consideration the effects of ply continuity between neighbouring discrete cells. As an output of this use case, the practice of evaluating each discrete cell relative to its neighbouring cells was introduced as a measure of manufacturability. This measure enabled structures to be improved and compared with respect to manufacturability.

3.3.2 Industrial case 2: Manufacturing analysis

A detailed design should be created with sufficient fidelity to ensure that all of the data required to manufacture the component is present. In order to ensure the correct constraints are accounted for, the thickness law data generated at the preliminary design stage is converted into a stacking sequence by following specific composite design rules. The design rules are typically applied cell by cell to the structure, and then the global design solution is checked.

There are 9 key composite design rules which can be applied to a composite structure design constructed from uni-direction material:

1. **Rule 1:** The laminate should be symmetric. A neutral axis can be imagined at the centre of the laminate, with equal quantities of plies above and below the neutral axis. The rule requires the ply orientations above the axis to

mirror the ply orientations below the axis. If perfect symmetry cannot be achieved, then non-symmetric plies should be moved as close to the neutral axis as possible. This is illustrated in Figure 16.

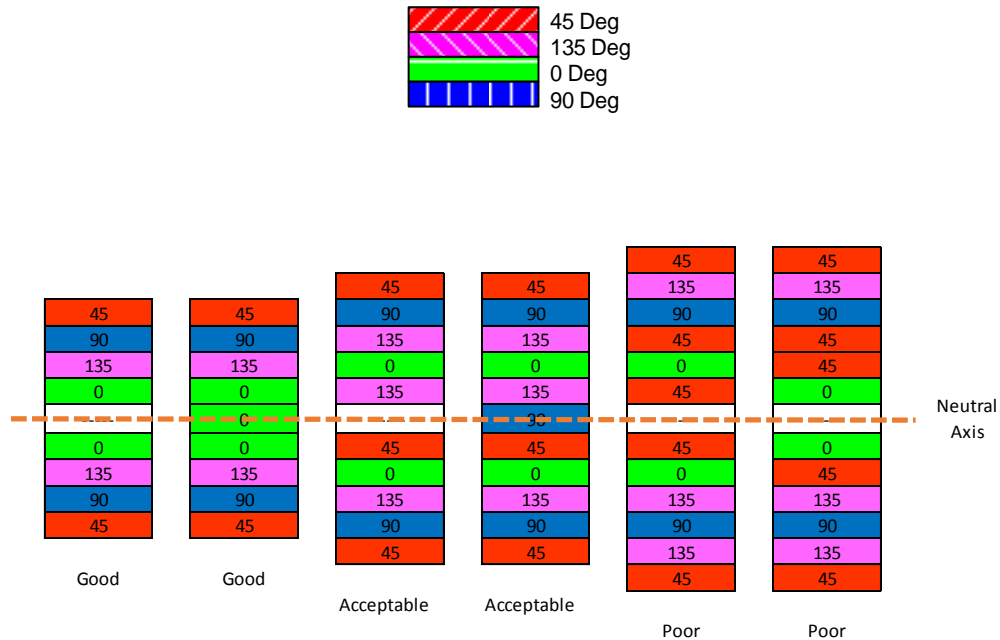


Figure 16: Examples of rule 1, Symmetry

- Rule 2:** The laminate should be balanced. To reduce the effects of an unbalanced laminate, two of the ply orientations that are perpendicular must be present in equal quantities, either 45 and 135 or 0 and 90 degree orientations. This is shown in Figure 17 using a ply design table.

Orientation	Quantity of plies		
0	10	10	10
45	15	15	12
90	2	10	8
135	15	4	10

Good Good Bad

Figure 17: Examples of rule 2, balanced laminate

- Rule 3:** No orientation should constitute less than 8% of the total thickness of the laminate, or more than 67%. This rule enables the design to

withstand the resultant compression load created by the poisson effect in a laminate. Typically the 0 degree orientation plies are aligned to the primary load direction and constitute the greatest percentage of the orientations in the laminate, and the perpendicular 90 degree orientation plies make up the minimum percentage plies in the laminate.

4. **Rule 4:** The outer plies should not be the same orientation as the main load bearing ply direction. This is due to increased likelihood of damage to the outer plies.
5. **Rule 5:** Try to avoid grouping plies with the same orientation. A stress optimised laminate may have a high quantity of plies in a specific orientation, but these should not be grouped together as this could increase coupling effects which may lead to stress concentrations inside the laminate.
6. **Rule 6:** Do not allow more than 3 plies of the same orientation to be sequenced next to each other. An equation is used for this rule:

$$n_{Max} = 4 \text{ plies} \approx 1.0\text{mm thickness}$$

Equation 1: Maximum number of adjacent same-orientation plies

7. **Rule 7:** To improve buckling performance, place 0 degree orientation plies as far away from the neutral axis as possible. This is due to the centre of the laminate not being in tension or compression whilst under a compressive load.
8. **Rule 8:** To minimise coupling effects, group 45 and 135 degree plies together in adjacent pairs, with symmetry around the neutral axis. This rule reduces laminate distortion.
9. **Rule 9:** To reduce inter-laminar shear effects, reduce the angle between the adjacent plies. Some plies may be coupled, such as 45 and 135 degree plies, so non-coupled orientations like 0 and 90 degree plies should be distributed with 45 and 135 plies between them to reduce the angle between the plies from 90 degrees perpendicular to only 45 degrees.

These 9 rules contain several contradicting instructions, making it difficult for a designer to apply them consistently to a design. To highlight this, the same example used in section 3.3.1 is taken from a preliminary sizing stage to a detailed design with the rules applied. This is illustrated Figure 18, visually highlighting the discontinuity of the different orientation plies between two cells which have the same thickness, same quantity of plies, but different ratios of the four principle orientations.

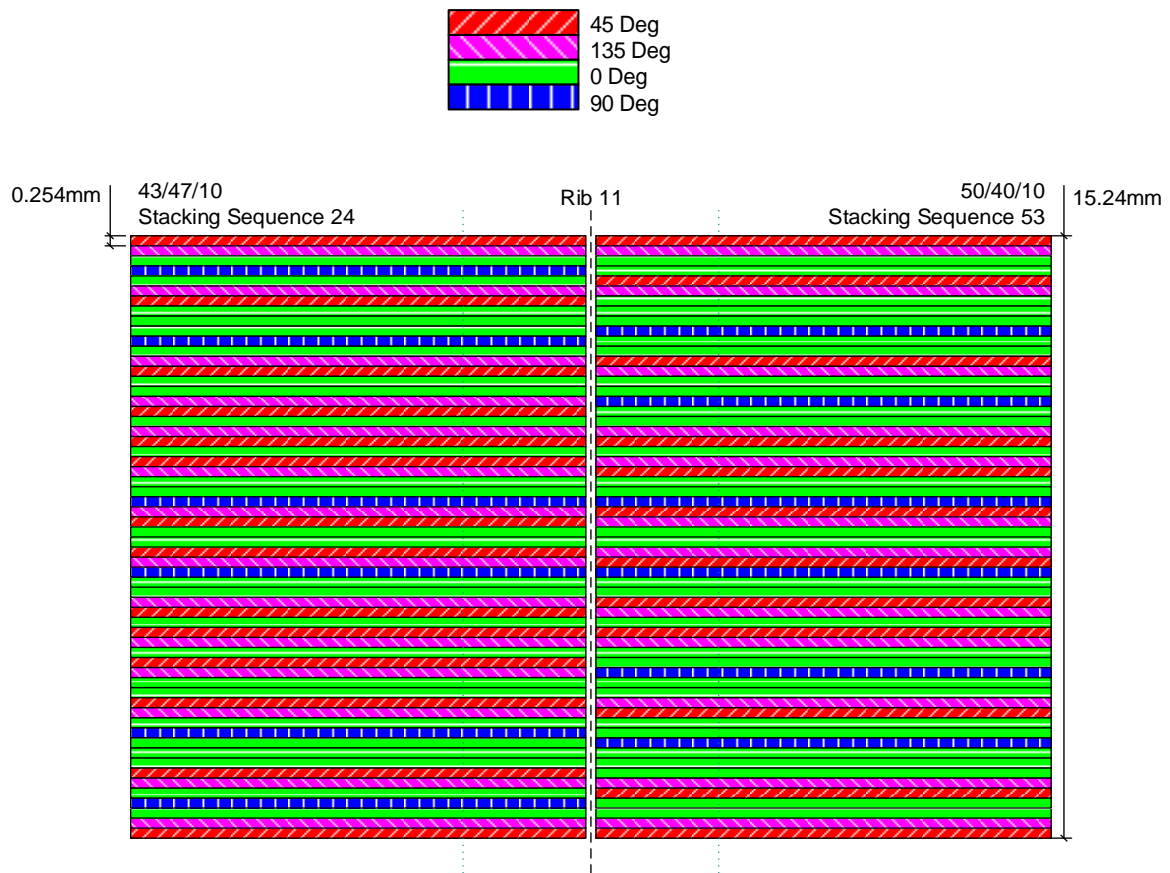


Figure 18: Example showing SS24 and SS53

The designer must now apply the design rules to the stacking sequences using a strategy that also improves the same-orientation continuity between the neighbouring cells.

The first five rules are already accounted for when the stacking sequences are automatically populated from the thickness laws in the CAD package. In this

instance CATIA V5 R21 was used to automatically convert the thickness laws into stacking sequences using the 'virtual stacking' tool in the composites grid workbench.

Rules 5 to 9 encourage the designer to re-sequence plies to suit structural performance requirements, so a designer will typically implement this in stages. Initially looking at coupled pairs of 45 and 135 degree plies, two pairs are identified in stacking sequence 24 and six pairs are identified in stacking sequence 53. The changes are highlighted in Figure 19 by shading them with darker colour, and placing a star next to them. Each pair of plies was re-sequenced to align with a pair of same-orientation plies in the neighbouring cell, improving the ply continuity. The position of the pair in the overall sequence was also improved. The result is an increase in continuous plies from 46 to 50 out of 60.

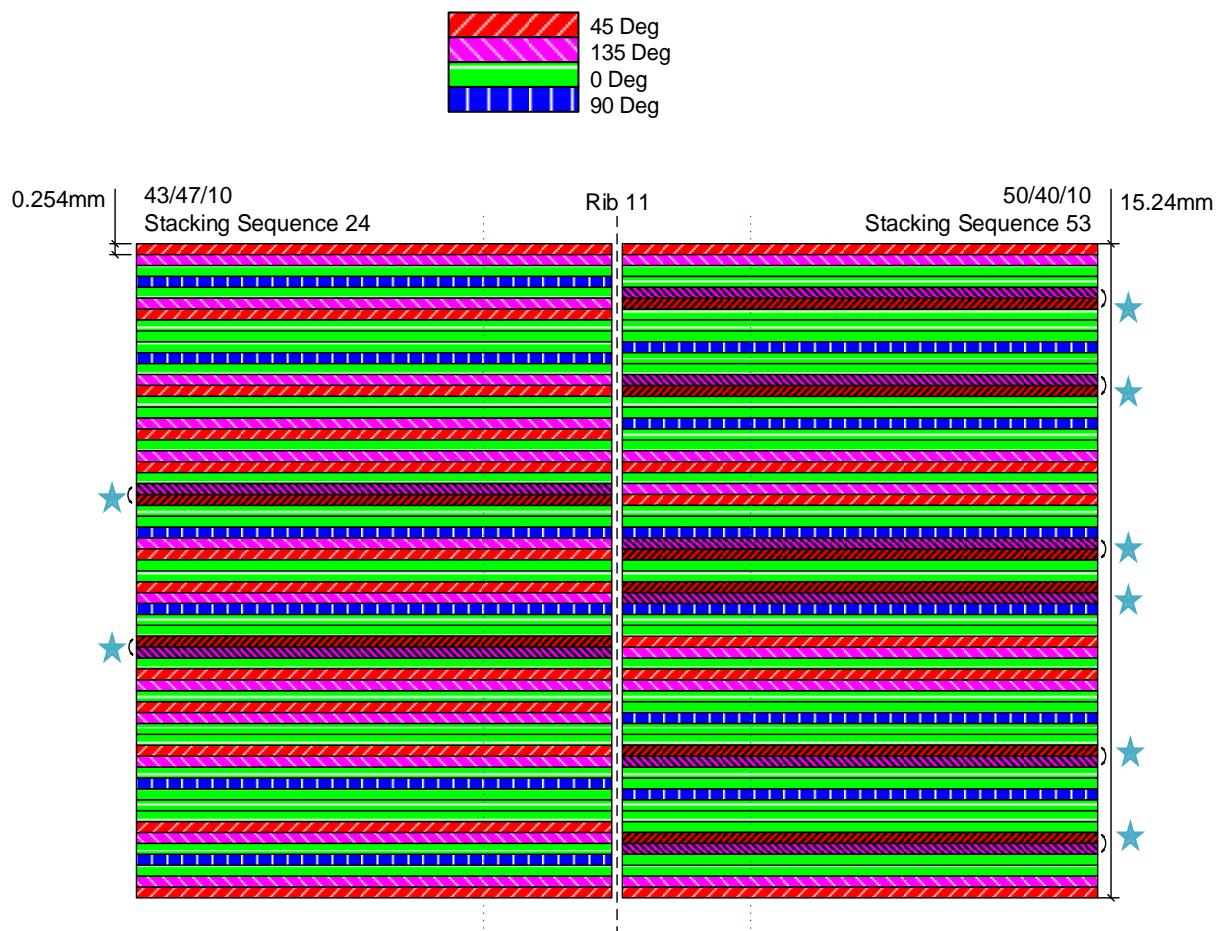


Figure 19: 45 degree and 135 degree plies re-sequenced

The next step is to evaluate the 0 and 90 degree plies which could be re-sequenced to improve continuity. Stacking sequence 24 has a 90 degree ply which is sequenced in a group of 0 degree plies which doesn't align with the neighbouring plies in stacking sequence 53. The stacking sequence 24 order in that area is 0/0/0/90/0 and the corresponding plies in stacking sequence 53 is 0/0/90/0/0, which gives a 4 out of 5 ply continuity, but changing sequence 24 to match sequence 53 increases the continuity to 5 out of 5 continuous plies. This is highlighted in Figure 20 by the plies marked with a star. The overall laminate continuity is now increased to 52 out of 60.

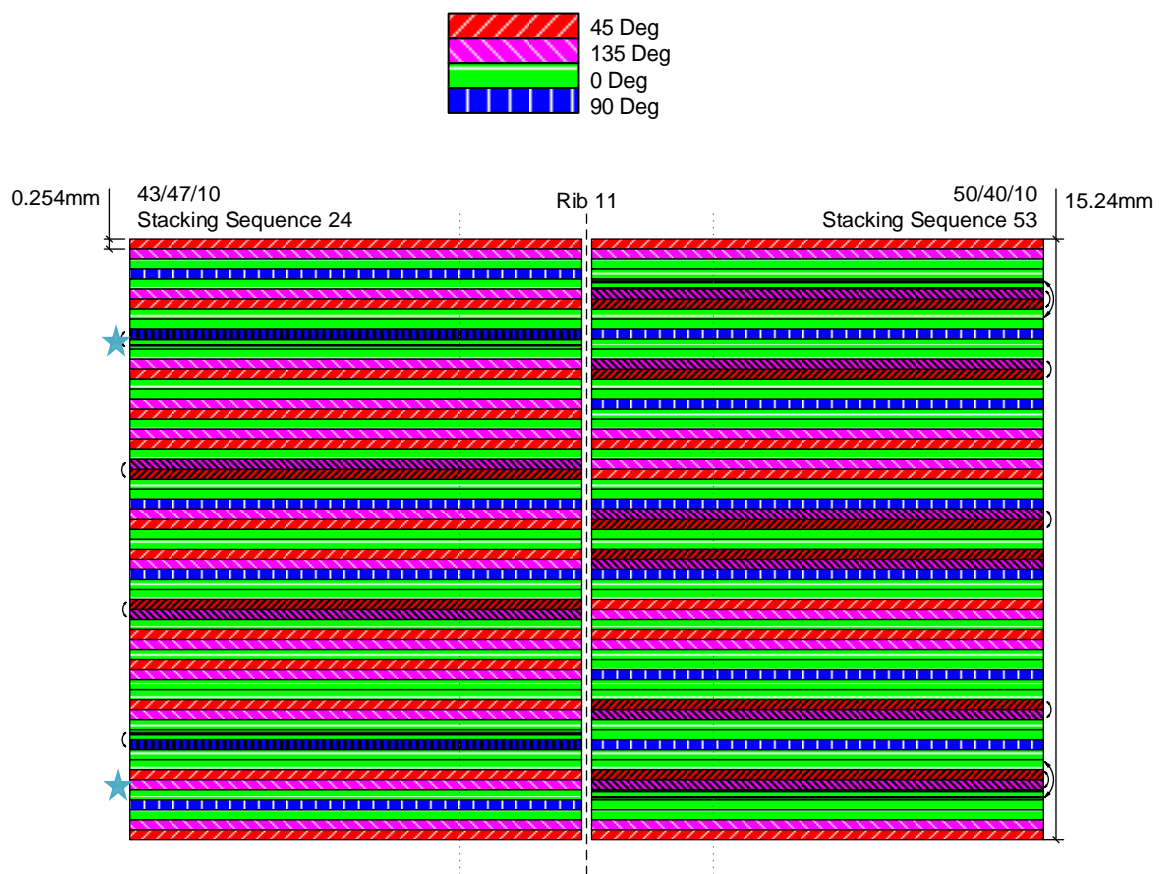


Figure 20: 0 and 90 degree plies re-sequenced

The non-continuous plies must extend into the neighbouring cell in order to effectively transfer load from cell to cell. This creates an overlap that is directly related to the non-continuous plies. The designer must therefore attempt to improve continuity in order to reduce the mass added by overlaps. Figure 21 illustrates the final solution after ply re-sequencing improvements have been

made. The overlap before re-sequencing was 18.796mm thick, representing a 3.556mm local increase in thickness. The resequencing activities have reduced this overall thickness to 16.764mm, which is an overall increase of only 1.524mm.

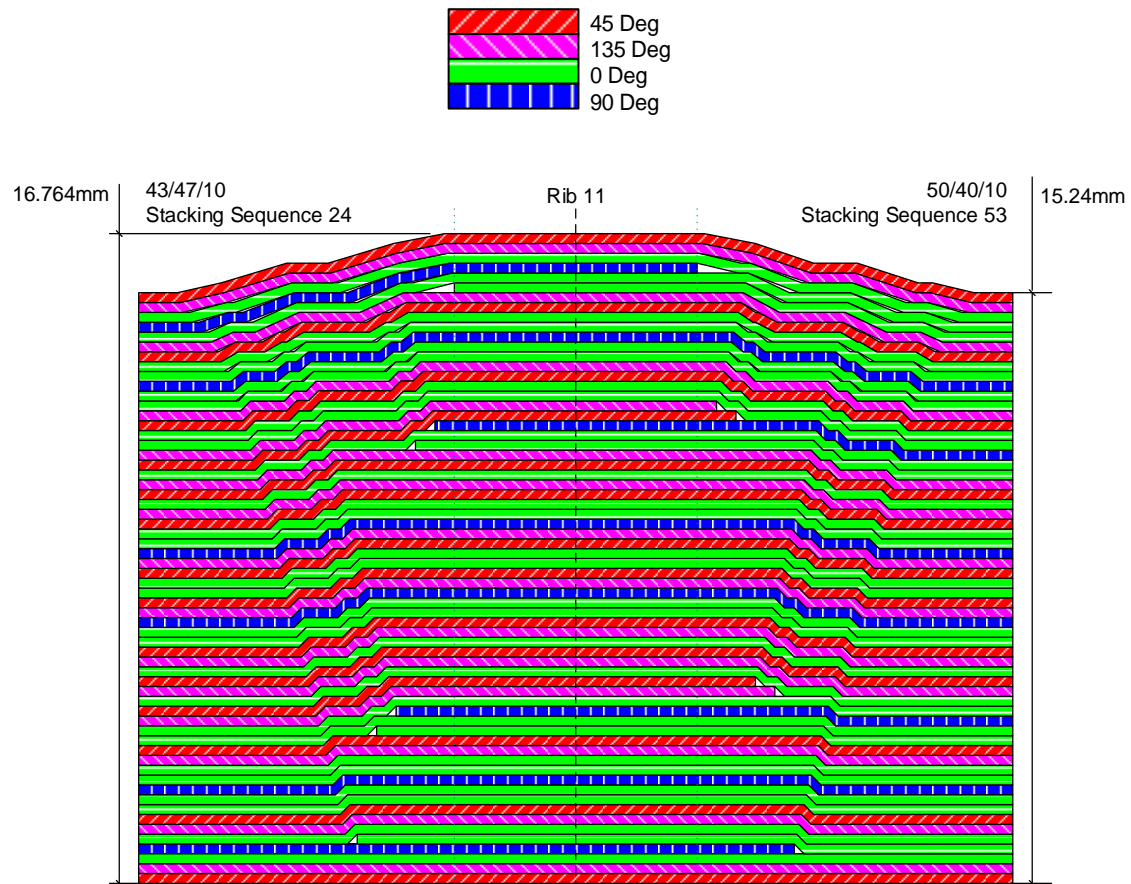


Figure 21: Overlap between SS24 and SS53 reduced by ply re-sequencing

In this use-case, only two adjacent cells have been considered to highlight the changes made by the designer in a simplified example. In order to apply this approach to a large composite structure, each individual cell needs to be compared with up to eight adjacent cells, and a typical wing or fuselage structure can have anywhere between 120 and 400 individual cells.

The main practices described in this section enable the design rules to be administered in a way that the effects on the manufacturing process can be identified, and then changes can be made to the stacking sequences to improve the manufacturability while still complying with the rules.

3.3.3 Industrial case 3: Design evaluation methods

The previous two use cases have identified some of the steps taken by designers to represent the original design intent whilst also increasing the design fidelity through the application of design rules, and also attempting to reduce the mass of the final design solution. Whilst these steps have accounted for the structural performance of composites, and the specific design rules required to define laminates, the practicalities of manufacturing the structures on an industrial scale have not been factored into the design. In order to do this, the layer by layer topology of the design must be evaluated with consideration given to the automated deposition systems that accurately place the layers of composite material on top of each other to build a 3D laminate.

This use case describes two approaches for evaluating the design for suitability of manufacture, firstly looking at the 2D shape of each ply, and secondly, looking at the cumulative effect of the ply shapes as a 3D surface.

All automated deposition systems can be described as end effectors which manipulate composite material, and an NC controlled machine which moves the end effector around the structure to enable material to be deposited in known locations, the way that the end effector works and the way that it is moved around the structure differ from machine to machine, and some technologies also integrate the motion of the structure into the deposition system. However, all systems are effected by the shape and profile of the ply that is designed, and a poorly designed ply can be impossible to manufacture because the profile is too complex for the end effector to access, or it can be inefficient to manufacture because the machine motion requires frequent stops, starts, slow movement or movement where no material is being deposited.

To highlight the effects that ply shapes have on automated deposition cycle times, two ply shapes with the same area but different ply boundary lengths are described. Ply A represents a rectangular grid of three by five cells, with an area of fifteen cells, and a perimeter of sixteen cell edges. Ply B represents a non-uniform grid with an area of fifteen cells and a perimeter of twenty cells. These two plies are illustrated in Figure 22.

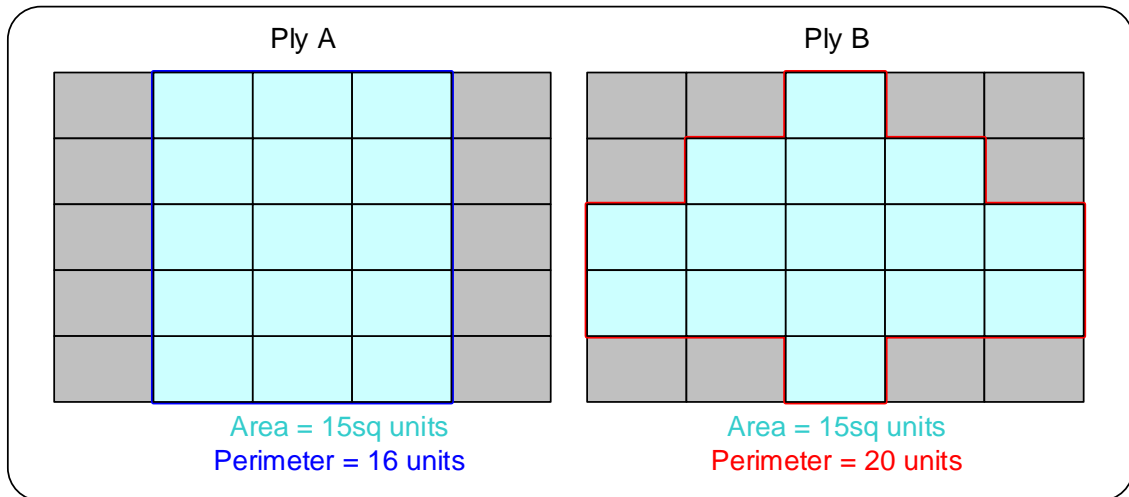


Figure 22: Example ply shapes with same area but different perimeter values

The perimeter of the ply is important for automated deposition systems because the systems need to slow down to cut and deposit the beginning and the end of tape course. The system also needs to turn or reposition after depositing the course in order to deposit the next course. Both of these functions cause the deposition system to slow down and operate at a reduced efficiency. Figure 23 illustrates an example machine path for a 0 degree ply A, with each cut and turn visually highlighted on the schematic.

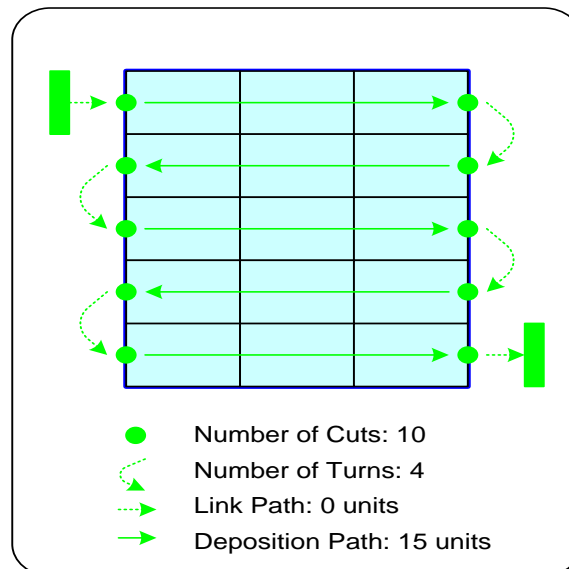


Figure 23: Visualisation of machine motion for 0 degree Ply A

Figure 24 illustrates an example machine path for a 0 degree ply B, with each cut and turn visually highlighted on the schematic.

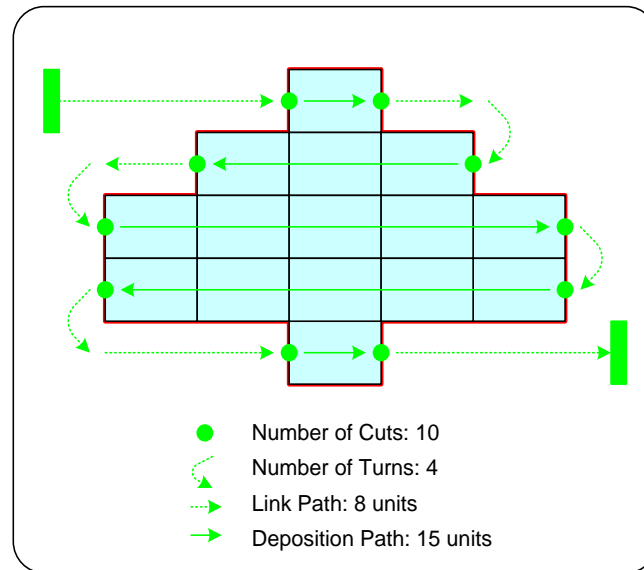


Figure 24: Visualisation of machine motion for 0 degree ply B

By comparison, both ply shapes have the same area and the same number of boundary cuts and turn-arounds, however ply B requires the machine to travel a greater distance between the end of one course and the beginning of the next course. The time when the machine is moving but not depositing material is referred to as 'non-productive time' and this increases the cycle time.

Deposition machines must slow down to perform complex tasks such as cutting the beginning or end of a course, or negotiating complex geometry. The machine velocity plays an important part in the efficiency of the production cycle. Reducing non-productive time improves deposition efficiency, but the machines can still deposit at sub-optimal speeds if the ply shapes do not allow them to accelerate to maximum speed before they are forced to decelerate to perform a cut or complex geometry manoeuvre.

Figure 25 shows a graph of machine velocity plotted against distance travelled for the 0 degree ply A. The long machine paths where material is deposited allow the machine to reach maximum velocity, the shorter peaks on the graph represent the short non-productive moves made to turn and reposition.

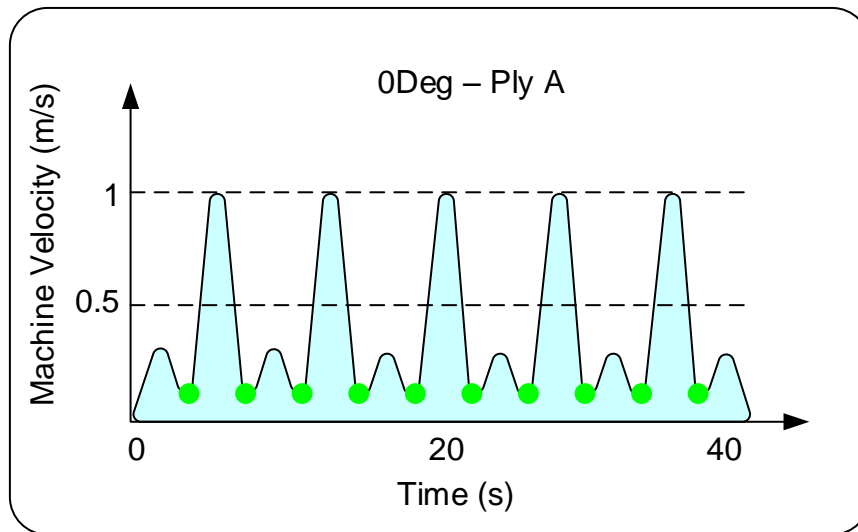


Figure 25: Visualisation of the machine velocity for 0 degree, ply A

Figure 26 illustrates the machine velocity plotted against distance travelled for the 0 degree ply B. The main difference that can be seen between ply A and ply B is that the ply B average machine velocity is lower. Frequent short movements result in the machine being unable to accelerate to full speed between features.

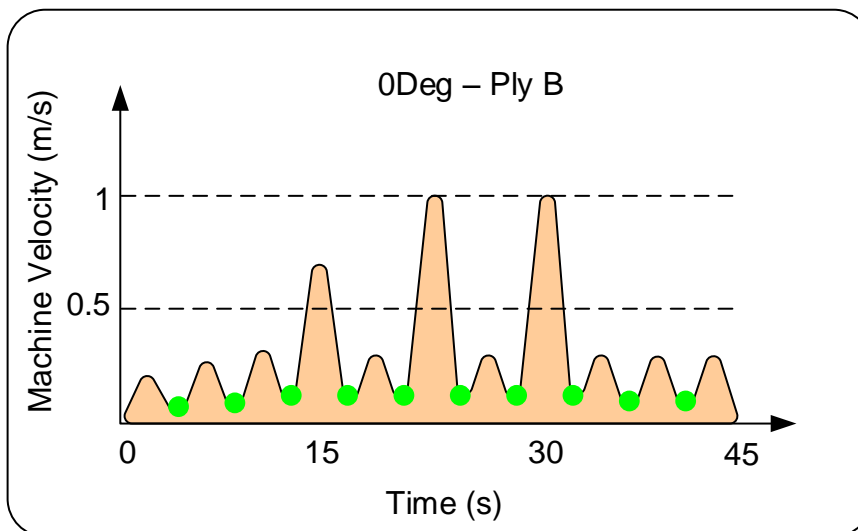


Figure 26: Visualisation of the machine velocity for 0 degree, ply B

The other ply orientations also produce similar results. Figure 27 illustrates a representation of the machine path for a 45 degree ply A, and Figure 28 illustrates the machine path representation for the 45 degree ply B.

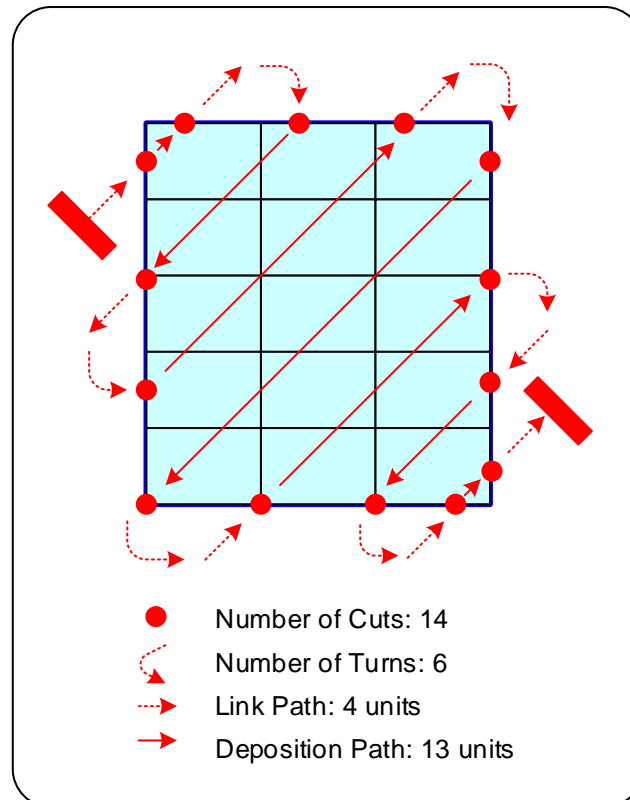


Figure 27: Visualisation of the machine velocity for 45 degree, ply A

The 45 degree ply A and B contain more cuts, turn arounds and non-productive motion for the same area and perimeter of the 0 degree ply versions.

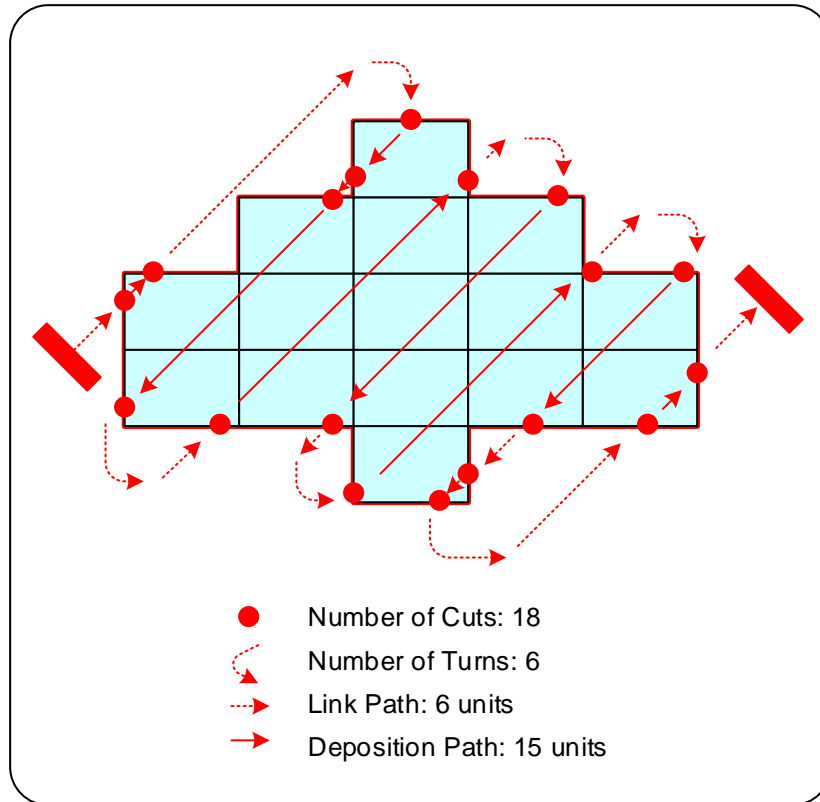


Figure 28: Visualisation of the machine velocity for 45 degree, ply B

For this use case, the components of the machine motion for ply A and ply B have been compiled for each of the principle four ply orientations and are shown in Table 11.

The generate comparative cycle times, the size of the cells and speed of the machine have been assumed as 1 cell taking 1 second to cover, and the effects of acceleration and deceleration have been ignored.

Table 11 highlights how the productive time between ply shapes A and B is similar (due to having the same area but no effects of acceleration or deceleration accounted for). The non-productive time for ply shape B is approximately 1/3rd greater than for ply shape A

Table 11: Components of machine time calculation for Ply A vs. Ply B

Ply Design	Orientation	Non-Productive Time (s)	Productive Time (S)	Total Cycle Time (S)
Ply Shape A	0	22	15	37
	45	36	13	49
	90	22	25	47
	135	36	13	49
	Total	116	66	182
Ply Shape B	0	30	15	45
	45	42	15	57
	90	45	24	69
	135	42	15	57
	Total	159	69	228

The reduced deposition speed is not only related to the ply boundary shape, but also the geometrical features generated by multiple ply boundaries laminating into a 3D feature such as a ramp.

The use case described in section 3.3.2 illustrated the creation of a 3D ramp feature forming on the boundary of two adjacent cells. A graphical representation of two adjacent cell boundaries, each featuring a ramp, is illustrated in Figure 29. This ramp feature creates a potential machine access problem for the deposition

end effector, which typically relies on a semi-rigid roller device to position and consolidate material onto the tool surface or existing laminate.

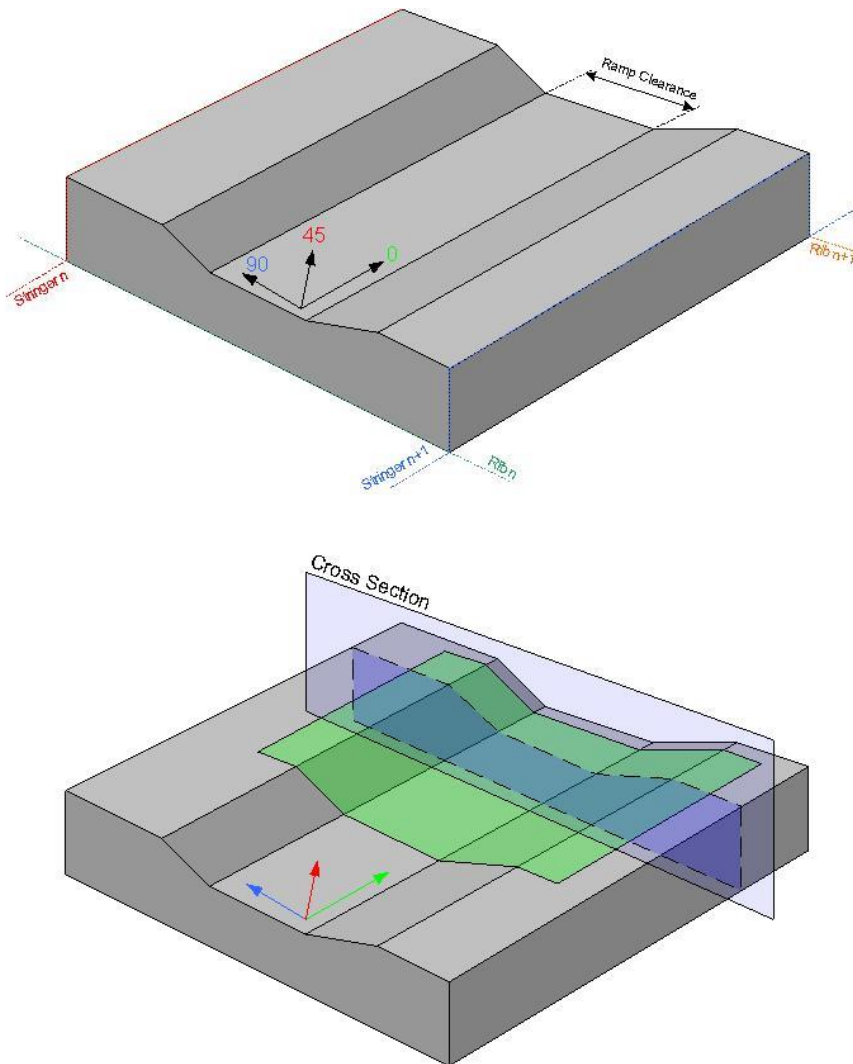


Figure 29: Representation of two ramp features creating a complex geometry

The angle of a ramp is determined at the detailed design stage of the lifecycle, however the height of the ramp is established in the preliminary design stage when the thickness laws are converted to stacking sequences. If the ramps become too tall or wide, then the 3D geometry created can become too complex for the deposition roller to access. Figure 30 illustrates a cross section between two ramps with the ideal ply conformity shown.

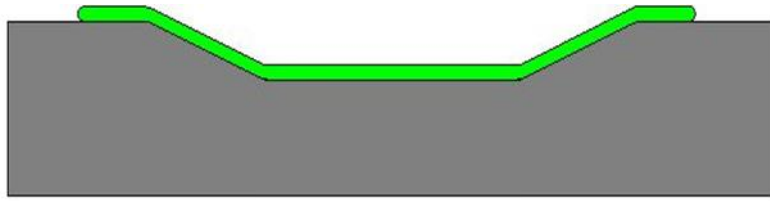


Figure 30: Cross section of two ramps, showing ideal ply conformance

Figure 31 illustrates how a deposition roller larger than the clearance between the ramps is unable to conform to the 3D geometry, and the material is not adequately consolidated causing a manufacturing defect.

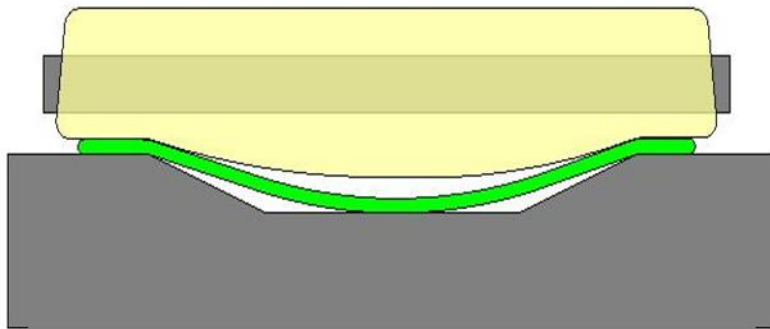


Figure 31: Roller unable to conform to geometry, leading to inadequate ply consolidation

In order to reduce the severity of the defect, in some instances the deposition roller can be manually reprogrammed during the manufacturing process so that less material is deposited, and only a fraction of the surface of the roller is used. Figure 32 illustrates only half of the material being deposited, enabling the roller to be re-positioned in an orientation that improved material consolidation.

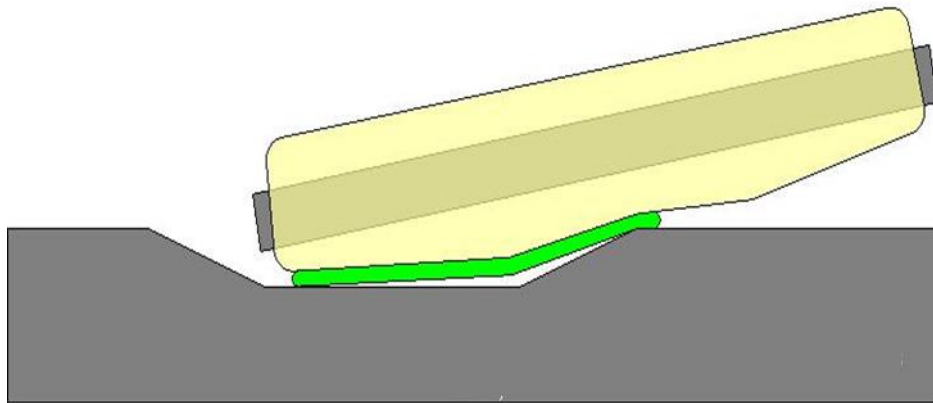


Figure 32: Improve ply consolidation, but at half deposition width

The drawback of halving the width of material deposited, is that the time taken to deposit a full width of material is doubled. The deposition machine must also reduce deposition speed when geometry is extreme as in this example. This highlights how the ply boundaries that cause ramp features can also have a negative effect on the cycle time of the automated deposition process, and in extreme cases, can prevent the structure from being manufactured due to the occurrence of unacceptable laminate defects.

This section describes the practice of modelling the effects of deposition machine motion for each ply shape and fibre orientation. The benefit of this practice is by enabling designed ply shapes to be changed with respect to the indicated production speed.

3.4 Concluding remarks

In this chapter, three industrially derived use cases have been described, each highlighting a different DFM challenge. In section 3.3.1 the methods used to size the structure locally using a cell-by-cell approach were described and compared with the global way that ply continuity between individual cells needs to be evaluated. In section 3.3.2 the composite specific design rules are described, and the ambiguity of the solution is highlighted by the unstructured methods that each individual designer uses to apply the same rules to different designs. Finally, in section 3.3.3 the manufacturing penalties for non-continuous plies are described

in the way of 3D ramps and ply boundary edge cuts, both negatively impacting production cycle times by reducing deposition speed.

The use cases highlight a problem that is apparent at a stage in the design lifecycle, but triggered by a decision made upstream in an earlier stage of the design lifecycle. Problems with locally optimised cells in the preliminary design stage not having adequate ply continuity are caused by a failure to evaluate structures globally at the conceptual design stage. The same pattern is true for detailed design, with the poor ply continuity and ramp features being seen at detailed design, but caused by the absence of ply continuity evaluation tools at the preliminary design stage.

With hindsight, it is relatively easy to see the source of errors in a high fidelity design, but when the design fidelity is low, the information available at the time does not intuitively highlight potential downstream problems to a designer. This conclusion supports the research aim of building a strategy to apply DFM to a design specifically using the tools used in early lifecycle stages, and considering an automated manufacturing process.

4 STRATEGIES TO APPLY DFM USING DIGITAL TOOLS

The aim of this chapter is to identify a way in which DFM can be applied using digital tools. The previous chapter highlighted the need to represent high fidelity manufacturing constraints at a much earlier stage of the design lifecycle where the design fidelity is very low, and in this chapter a strategy to achieve this for an aerospace structure is described using an industrially relevant use-case and physical validation trials. The research described in this chapter has been published as a journal article by the author [95].

4.1 Introduction

In section 3.3 the three example use cases described how the shape of each ply created during the preliminary design stage influenced the ply continuity, the manufacturing process speed and the additional mass added to the design during the downstream processes. These three DFM issues become areas to address at the preliminary design stage.

4.1.1 Ply continuity

During the preliminary design stage, the structure is optimised for material thickness and distribution of fibre orientations using a local cell by cell approach. It is only at the detailed design stage that the discrete cells are joined together and the distribution of the fibre orientations is adjusted to improve continuity [8]. An alternative approach is to perform the ply continuity adjustments during the preliminary design stage.

The ply continuity requires the ply stacking sequences to be defined, but the definition of these stacking sequences requires no other input than the thickness laws already defined and the design rules that were defined in section 3.3.2. A theory can therefore be tested where automating the generation of stacking sequences, and improving the ply continuity could be achieved during the preliminary design stages [95].

4.1.2 Manufacturing process speed

The manufacturing process speed is linked to the ply continuity because the ply boundaries cause the deposition system to slow down to make the cut, and then where a cut is made inside the overall component perimeter. Multiple cuts that build up through the laminate in the same area lead to a ramp, which also causes the deposition system to slow down. The theory that the simulated deposition of different ply shapes can be evaluated against the degree of ply continuity between neighbouring cells in the ply definition table can be evaluated with a use-case example [95].

4.1.3 Added mass

The preliminary design assumes that all plies of different orientation join at the cell boundaries. However, for the loads to be transferred efficiently between discontinuous plies in neighbouring cells, they must be extended into the neighbouring cell as an overlap. The overlaps then need to be extended by different lengths in order to build up a gradient, and these overlaps add additional mass to the preliminary design which is not accounted for in the structural evaluation.

When the design rules are applied to a laminate, it is sometimes necessary to add in an additional ply to satisfy specific rules such as symmetry. In these cases, the thickness locally increases, and the thickness law changes, resulting in increased mass.

4.2 Methods followed to apply DFM using digital tools

A method was defined in this research to describe the strategies to apply DFM using digital tools. The method was identified by isolating the key process steps required to manufacture a composite laminate using an AFP machine. When the objective is to produce a physical component using an AFP machine, then the previous process steps can be identified.

Prior to manufacturing a part using an AFP machine, the AFP machine requires a digital program to control the machine motion during material deposition. The

program is created using software that allows the programmer to visualise the machine motion. This digital simulation enables all of the machine motion to be calculated in a 3D environment from a detailed design, and therefore a simulated deposition time can be generated for any given component. The digital simulation is dependent on detailed CAD data though, so a prior step is also required to perform a manufacturing assessment using the preliminary design data that the detailed design is based upon.

The low fidelity preliminary design data can be used to indicate the manufacturability of the component prior to the completion of higher fidelity detailed design stage and the simulation of the AFP process.

The steps followed in this research are:

1. **Identify a method to measure ply continuity in a sizing array.** Because the 3D CAD model will not exist in the early stages of the design lifecycle, the method must be applied to a cell-by-cell array of ply data. This is demonstrated using some small ply shape examples. The benefit of creating a method based on lower fidelity early-lifecycle data is the ability to evaluate a design for manufacturability prior to incurring further costs to increase the design fidelity.
2. **Test ply continuity measures against a simulated 3D model.** The transition between a sizing array and a 3D model needs to be evaluated so that the increase in design fidelity can be accounted for. Once the array of ply data is measured for continuity, the designs must be scaled up to 3D models and evaluated using manufacturing simulation software. Several ply shape examples with different levels of shape complexity and ply continuity, but the same area, are used as use-cases.
3. **Validate ply continuity measures with the manufacture of physical parts.** The designed use cases are then physically manufactured to establish real-world cycle times, validating the simulations and the ply continuity evaluation carried out using only the array of ply shape data from the preliminary design stage.

In summary, small-scale use-cases are described to demonstrate the methods and tools used to evaluate ply continuity scoring at different stages of the design lifecycle.

4.3 Early lifecycle manufacturing evaluation

The trends identified in surveyed literature described in section 2.7, and the industrial practice described in section 3.4, suggested that the earliest that an estimation of the automated deposition cycle time can be produced is when a laminate detailed design can be used to run a digital process simulation. The drawback of using a digital process simulation is the requirement of the digital tools to run from a detailed laminate CAD model, which is labour intensive to produce. It is therefore very desirable to be able to perform a lightweight simulation or estimation of the production process cycle time before any effort is committed to creating a detailed design of the laminate. The following example evaluates an opportunity to model the conceptual laminate design as a series of simplified 2-dimensional arrays, or tables, specific to each layer in the laminate, and then draw comparison between the area and boundary length of each layer relative to a detailed design, simulation and physical ply layer manufacture.

Representing the laminate with a simplified 2-dimensional array for each ply has been adopted because the approximate shapes are very similar to the structural model of an aircraft structure such as a wing skin or fuselage panel. The sizing data is stored in a compatible format.

Zone X in Table

[Bound by V2, H1, V4, H3]

Zone Y in Table

[Bound by V5, H1, V7, H6]

	V1	V2	V3	V4	V5	V6	V7
H1	12	14	14	13	16	16	13
H2	12	14	14	13	16	16	13
H3	12	12	12	13	16	16	13.5
H4	12	12	12	13	16	16	13.5
H5	12	12	12	13	16	16	13.5
H6	12.5	13.25	13.25	13	13	13	13
H7	15	15	15	15	15	15.25	15.25
H8	15	15	15	15	15	15.25	15.25
H9	12.5	13.25	13.25	13.5	13.25	13.25	13.25
H10	11.5	11.5	11.5	11.5	11.5	11.5	11.5
H11	11.5	11.5	11.5	11.5	11.5	11.5	11.5
H12	11.5	11.5	11.5	11.5	11.5	11.5	11.5
H13	11.5	11.5	11.5	11.5	11.5	11.5	11.5
H14	11.5	11.5	11.5	11.5	11.5	11.5	11.5
H15	11.5	11.5	11.5	11.5	11.5	11.5	13.25
H16	11.5	11.5	12.75	12.75	12.5	12.5	13.25
H17	13.25	13.25	13.25	13.25	12.5	12.75	13.25
H18	13.25	13.25	13.25	13.25			

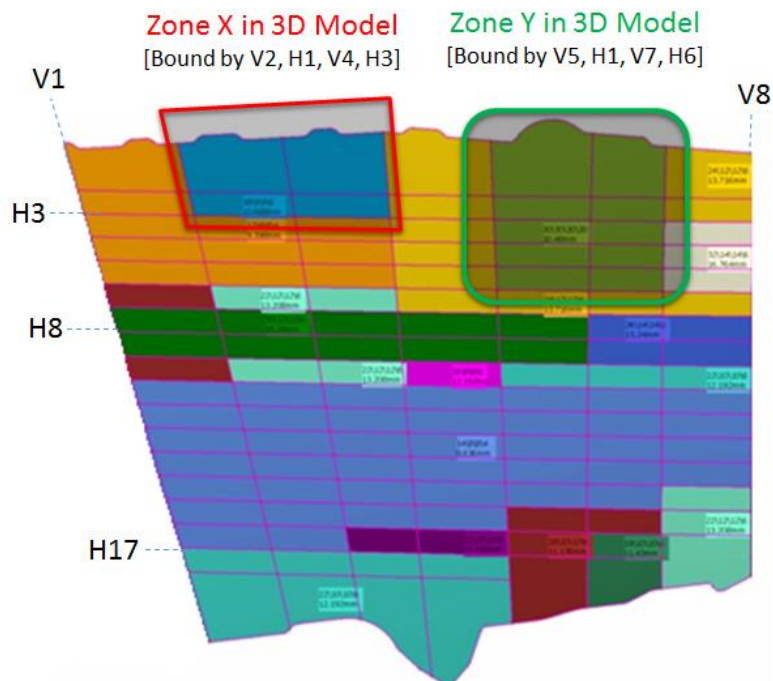


Figure 33: Translation of 2D array (a) of sizing data to a 3D ply shape model (b)

In Figure 33 illustration (a) represents a table which records the intended thickness of each cell in the panel, and this can be directly mapped between the CAD model (b) which is a surface with 3D geometry and ply data attributed to it, illustrated as a top-view and. Figure 34 illustrates a 45 degree ply from the laminate shown in Figure 33(a) and the approximate shape of the ply in table format.

	V1	V2	V3	V4	V5	V6	V7
H1		x45	x45	x45	x45	x45	x45
H2		x45	x45	x45	x45	x45	x45
H3				x45	x45	x45	x45
H4				x45	x45	x45	x45
H5				x45	x45	x45	x45
H6		x45	x45	x45	x45	x45	x45
H7	x45	x45	x45	x45	x45	x45	x45
H8	x45	x45	x45	x45	x45	x45	x45
H9			x45	x45	x45	x45	x45
H10							
H11							
H12							
H13							
H14							
H15							x45
H16			x45	x45			x45
H17	x45	x45	x45	x45		x45	x45
H18	x45	x45	x45	x45			

Figure 34: Sample ply representation generated from laminate sizing data

This excel based table representation of each ply area coverage allows a designer to make changes to the laminate definition before progressing to a 3D CAD laminate model. The 2D array format is common with most outputs from grid-based structural optimisation tools. The manufacturing constraints, in the form of machine motion for each ply shape therefore need to be represented in this style table format for the ply shapes.

Production speed improvement for an AFP machine requires the amount of time that the AFP machine is laying at full speed to be increased, while the time that the machine accelerates, decelerates and moves from position to position without laying material needs to be reduced.

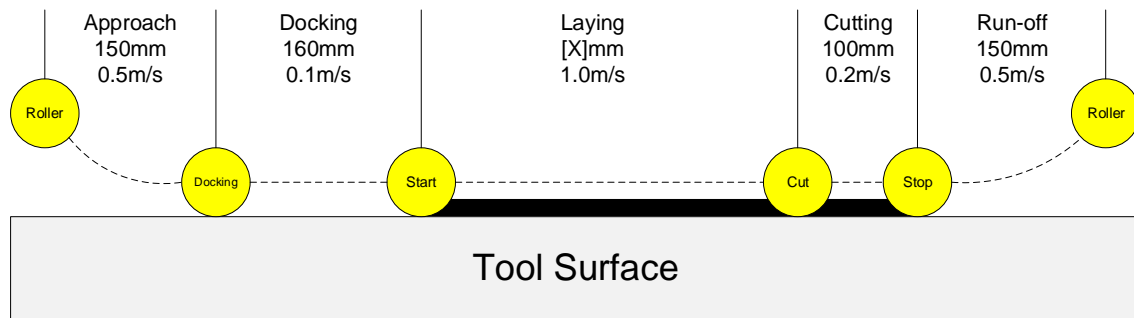


Figure 35: Schematic of NCC's deposition machine motion

The typical machine motion for laying a course of material over flat component is shown in Figure 35. The machine accelerates along the tool surface until it approaches the start of the ply, at this point the machine slows down as it feeds material onto the roller. The machine accelerates up towards maximum deposition speed. The machine motion then decelerates as it approaches the end of the ply boundary so that the material can be cut. If the flat component had a ramp feature in the centre, then the machine would also decelerate to negotiate the ramp feature at a slower speed.

The deceleration can be directly linked to the ply boundary where the machine trajectory is slowed down to perform cutting, turning or non-value-add motion moving to the start of the next course. This suggests that a ply with large surface area coverage, but a small perimeter boundary will be faster to produce than a cell with smaller area coverage and a larger ply perimeter, or a fragmented ply shape with high complexity and high aspect ratio. In these cases, a designer can improve the manufacturing speed by reducing the amount of distance that an AFP machine must travel without depositing material, as this is non-value added in the cycle time.

4.3.1 Developing a ply continuity representation

For each ply in the laminate the fibre direction is identified, and the cells can be assumed to either contain or not contain material occupancy. By moving through the cells in the array one-by-one, the comparison of each cell to its neighbouring cell can establish if a ply boundary is present, or if the cell is continuous with its neighbouring cells. Looking at each ply as an array and building a score that

represents the ratio of number of boundaries by the number of cells occupied by material allows a designer to create a numerical ply continuity score for each ply shape generated.

The concept of cell occupancy was established as a result of excel tables being used to represent ply shapes prior to creating 3D CAD geometry. The size of each cell was not known until the CAD geometry was defined. At the conceptual stage of the design lifecycle, the occupancy of the cell relative to its neighbours could quickly and easily be measured and influenced.

The continuity score is calculated according to the following rules:

1. In a given direction, each cell with the same occupancy will contribute a score of one to the tally.

$$C_{Direction} = \text{Number of cells inline} \times 1$$

Equation 2: Ply continuity score for filled cells

In a cell-by-cell move in the given direction, any change in the occupancy status reduces the directional continuity score tally by one.

$$C_{Changes} = C_{Changing\ Cells} \times -1$$

Equation 3: Ply continuity score for empty cells

2. The total tally is obtained by multiplying all directional tally.

$$C_{Total} = [C_{Direction\ 1} + C_{Changes\ 1}] \times [C_{Direction\ 2} + C_{Changes\ 2}]$$

Equation 4: Ply continuity score total

This is illustrated in Figure 37 and Figure 38, with a worked example shown in Figure 39.

An approximation error exists because the method does not account for true 3D ply shapes, only a 2D approximation with no reference to the dimensions of the cells, which may not be square in the 3D design. There is also a likely error derived from not being able to predict the behaviour of the machine at each boundary interface. The method does not distinguish between a machine turning, cutting or moving at a boundary.

Given a regular arrangement of grids where:

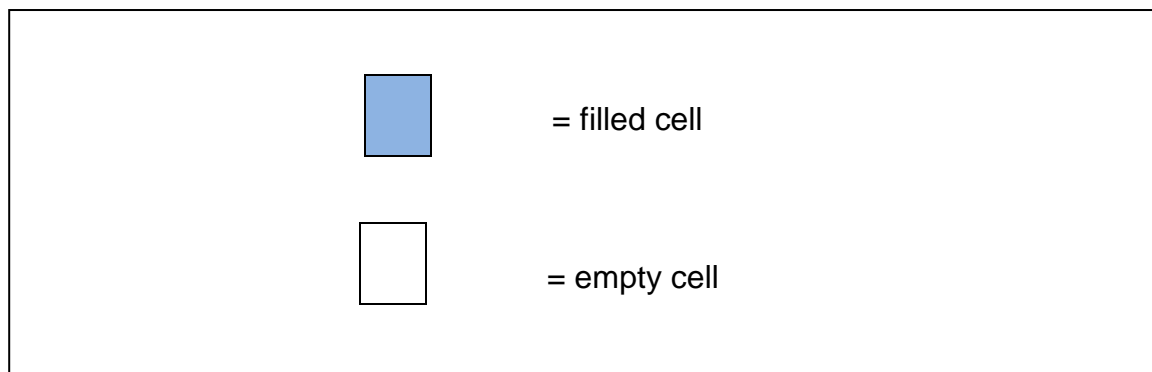
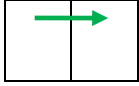


Figure 36: Representation of filled and empty cells

Continuity Scoring is calculated on a ply-by-ply basis, with the cell as the lowest unit. Cells have occupancy status, they can be filled or empty. Every cell will have an adjacency (neighbourhood) relationship with other cells.

- An adjacency relationship between two cells having the same occupancy status will contribute positively to the ply-based continuity scoring register.
- An adjacency relationship between two cells of differing occupancy status contributes negatively to the register.

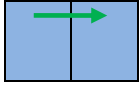
For a group of two cells where the ply direction and machine motions is moving horizontally from left to right (borders that trigger reductions are marked in red).



= two empty adjacent horizontal cells, $C_{Horizontal} = 2$

$$C_{Horizontal} = 2_{Inline} - 0_{Changes} = 2$$

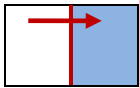
Equation 5: Formula for two adjacent empty horizontal cells



= two filled adjacent horizontal cells, $C_{horizontal} = 2$

$$C_{Horizontal} = 2_{Inline} - 0_{Changes} = 2$$

Equation 6: Formula for two adjacent filled horizontal cells



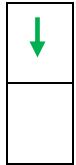
= two adjacent cells with differing occupancy status, $C_{horizontal} = 1$

$$C_{Horizontal} = 2_{Inline} - 1_{Changes} = 1$$

Equation 7: Formula for different horizontal cell occupancy

Figure 37: Representation of different horizontal continuity scenarios

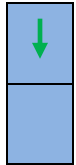
The same rules also apply for vertical adjacency checks, although the ply direction and therefore the machine motion direction is horizontal, so the vertical scores are halved.



= two empty adjacent vertical cells, $C_{Vertical} = 2$

$$C_{Vertical} = 2_{Inline} - 0_{Changes} = 2$$

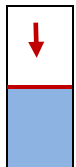
Equation 8: Formula for two adjacent empty vertical cells



= two filled adjacent vertical cells, $C_{Vertical} = 2$

$$C_{Vertical} = 2_{Inline} - 0_{Changes} = 2$$

Equation 9: Formula for two adjacent filled vertical cells



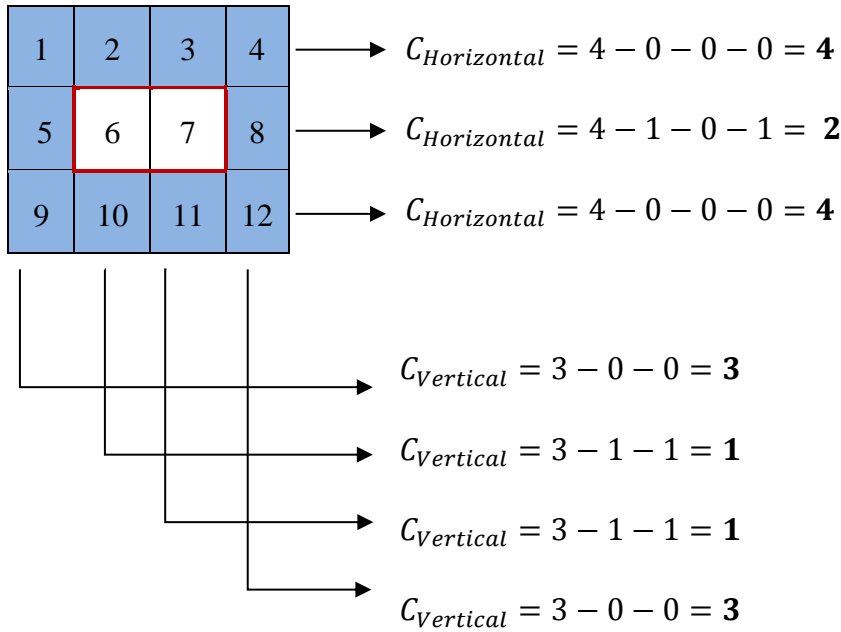
= two adjacent vertical cells with different occupancy, $C_{Vertical} = 1$

$$C_{Vertical} = 2_{Inline} - 1_{Changes} = 1$$

Equation 10: Formula for different vertical cell occupancy

Figure 38: Representation of different vertical continuity scenarios

4.3.2 Worked example of ply continuity scoring



$$C_{Total} = [4 + 2 + 4] \times [3 + 1 + 1 + 3] = 80$$

Figure 39: Example ply continuity calculation

Figure 39 shows a 12 cell array scoring 80 from a potential 144, so the continuity score for this shape is 55%.

$$Ply\ Continuity\ Score\ \% = \frac{Calculated\ score}{Maximum\ available\ score}$$

Equation 11: Equation to calculate ply continuity score as a percentage

In this example, the indicator of machine deposition speed is a summation of the ply continuity score for each of the plies in the laminate, represented as a percentage. An actual time is not calculated, as this method is only appropriate to compare two designs to establish which option is likely to be faster to manufacture.

The approach of comparing two very low fidelity concepts enables a direct comparison to be made between multiple concepts using the same assumptions,

but a a very early stage in the design lifecycle prior to any 3D CAD geometry being created.

The ply continuity score can be easily automated to score sizing data which is tabulated in an array, but it does not account for real life geometry due to the absence of any 3D CAD geometry at this early stage of the design lifecycle. Figure 33 shows the visible difference in size of the cells when data is translated from the table of uniform cells to a 3D CAD model. An alternative measure is to look at ply complexity instead.

Ply complexity is a ratio of the perimeter of the ply boundary to the area of the ply and is based on the tacit knowledge that this ratio influences manufacturing process i.e. the more complex the shape of a ply the more time it takes to lay that shape because the machines have to slowdown to make the necessary material cuts.

The equation to calculate the complexity score for a given ply is:

$$Ply\ Complexity\ \% = \frac{Ply\ Area}{Ply\ Perimeter}$$

Equation 12: Ply complexity equation

For the two sample ply shapes shown in Figure 22, ply A and ply B, the complexity score can be calculated as:

$$Ply\ A\ Complexity = \frac{15}{16} = 93.75\%$$

$$Ply\ A\ Continuity = \frac{15 \times 15}{225} = 100\%$$

Equation 13: Ply evaluation for ply A

$$Ply\ B\ Complexity = \frac{15}{20} = 75\%$$

$$Ply\ A\ Continuity = \frac{19 \times 17}{625} = 52\%$$

Equation 14: Ply evaluation for ply B

Although the ply complexity scoring mechanism is enables rapid evaluation of various play shapes, the main limitation is that it does not fully account for the actual complexity of automated manufacturing process.

4.4 Validation of the strategy using higher fidelity design data

In order to test the method of scoring the continuity of plies as an indication of cycle time, four laminate panels were designed and scored using the ply continuity method. These laminates were then modelled in CATIA V5 Release 19 and their automated manufacture was simulated using software from MAG Cincinatti called ACES v2 to derive a predicted cycle time for AFP manufacture.

The simulation approach enabled the flat coupons to be modified to suit curved tooling surfaces and also scaled to a larger size to establish if the effects of ply shape complexity scaled proportionally with ply size and ply geometry.

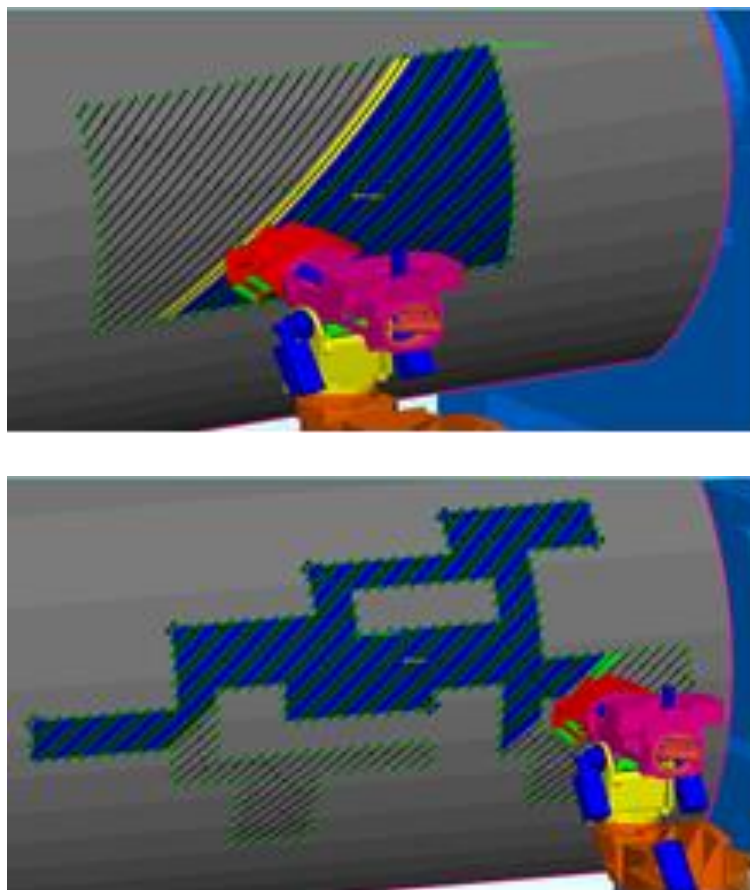



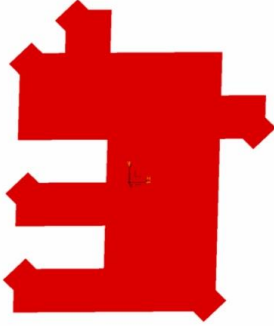
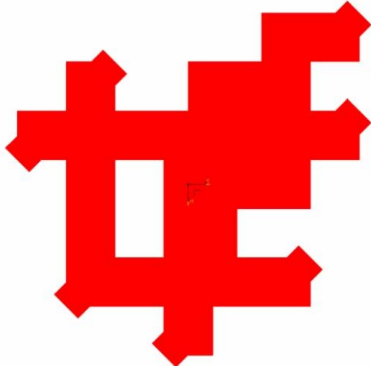
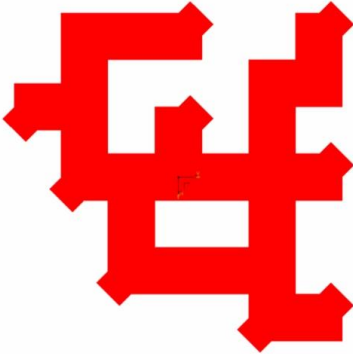
Figure 40: Visualisation of the AFP program simulation software being run on two different ply shapes, on a curved tool surface representative of a fuselage

All four laminates have the same surface area and the same number of plies and ply orientations. Only the boundary of the laminate was changed each time to increase the complexity and fragmentation of the ply shapes. The first, simplest and last, most complex coupons are illustrated in Figure 40 showing the simulation being visualised on a curved surface.

4.4.1 Validation results

The coupon ply shapes are shown (for a 45 degree ply) in Table 12.

Table 12: Coupon shapes based on 45 degree ply

 <p>Coupon 1</p> <p>The shape of coupon 1 is intended to create the most simple ply contour possible.</p>	 <p>Coupon 2</p> <p>The shape of coupon 2 is based on coupon 1 but features two perimeter areas where material is removed, and two where material is added. The design has the same area as coupon 1.</p>
 <p>Coupon 3</p> <p>The shape of coupon 3 is based on coupon 1, and includes a hole cut from the centre of the ply in addition to perimeter features where material is removed and added. The hole in the centre is not affected by minimum cut length constraints. The design has the same area as coupon 1.</p>	 <p>Coupon 4</p> <p>The shape of coupon 4 is based on coupon 1 but is entirely fragmented so that no cell in the array has full adjacency. The shape still includes a hole and the area is designed to be the same as coupon 1.</p>

The coupons were digitally simulated to obtain estimated cycle times and the results are shown in Table 13. This shows that when the area of each coupon is kept constant, but the complexity is changed to increase the length of each ply perimeter, the machine deposition time increases. ACES v2, configured with Coriolis machine parameters was chosen to perform these simulations.

Table 13: Simulation results for 4 coupons

	Ply Perimeter Length (mm) / Area (m ²)	Ply Complexity Score	Ply Continuity Score	Simulated Cycle Time (S)
Coupon 1	2705 / 0.427	16%	100%	1692
Coupon 2	4606 / 0.435	9%	75%	2268
Coupon 3	5699 / 0.437	8%	50%	2628
Coupon 4	6974 / 0.441	6%	34%	3132

The manufacturing process simulation results show that each method of evaluating manufacturing complexity is able to generally predict the correct trend, where increased complexity is relative to longer production cycle times, however the different methods do not accurately align. This is illustrated when the simulated cycle time for each successive component is plotted against ply continuity scores and ply complexity scores. This is shown in Figure 41, with the coupons being represented in the X axis as a coupon perimeter divided by the coupon area. This measure was selected as very small fluctuations in the coupon area were present due to the addition of material required to suit the AFP process known as minimum cut length, MCL, extensions. The values from the simulation are averaged from the manufacture of 4 ply orientations for each shape, 0 degree, 45 degree, 90 degree and 135 degree.

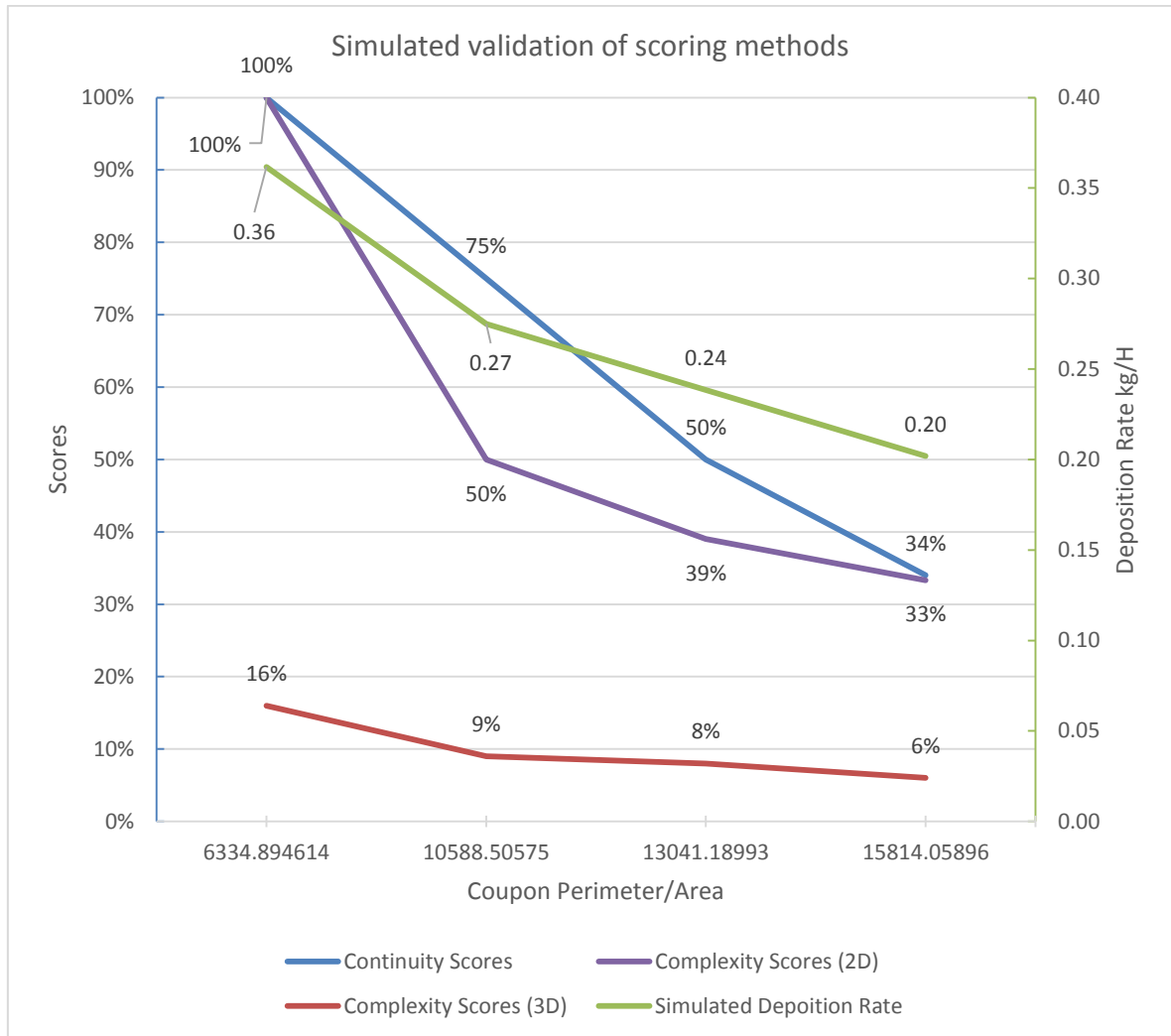


Figure 41: Graph showing simulated deposition rate, continuity score and complexity score per coupon

The continuity scores are close in value to the deposition rates generated using simulation tools. The complexity scores were generated twice, once using only the 2D sizing data prior to the 3D ply design being created, and then at a later stage in the design lifecycle using the 3D data from the ply design. All three methods for scoring the ply shapes predicted the correct trend in decreasing deposition rate. The ply continuity method and 2D ply complexity scores obtained similar trend profiles, but the 3D complexity score predicted the closest trend profile to the simulated data.

4.5 Validation of the design using physical trials

The four coupons were manufactured using a Coriolis AFP machine to obtain accurate and realistic cycle times to validate both the simulation results and the ply continuity scores. An example of coupon 4 at each stage of the life cycle is shown in Figure 42.




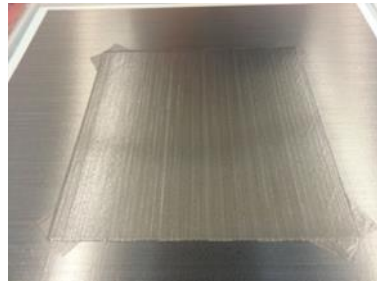




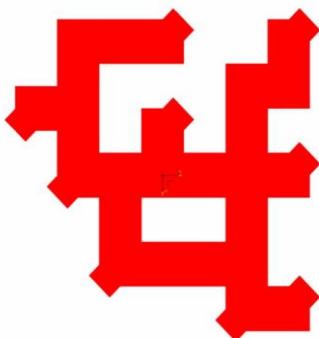

Figure 42: Coupon 4, design lifecycle from preliminary design to manufacture

4.5.1 Definition of the physical trial coupons

Each of the four coupons transitioned from a preliminary 2D design in excel, through to a CAD model in CATIA with 3D geometry and ply definitions, and then finally each coupon was manufactured as a laminate with each of the principle fibre orientations, 0 degree, 45 degree, 90 degree and 135 degree.

The definition of the coupons is shown in Table 14, with the design shown in 2D, virtual 3D and then real life 3D for each coupon. The increase in fidelity between the designs can be seen with the additional corner material representing the extra material that must be added to diagonal corners to satisfy the minimum cut length requirements of the AFP machine. The minimum cut length is not factored into the 2D design, but it appears in the CAD design and has the effect of altering the ply perimeter length and surface area ratio.

Table 14: Table showing stages of design for each coupon

Preliminary Design	Detailed Design	Manufactured Component																																																																
<table><tr><td></td><td>V1</td><td>V2</td><td>V3</td><td>V4</td><td>V5</td><td>V6</td><td>V7</td></tr><tr><td>H1</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr><tr><td>H2</td><td></td><td></td><td>1</td><td>1</td><td>1</td><td>1</td><td></td></tr><tr><td>H3</td><td></td><td></td><td>1</td><td>1</td><td>1</td><td>1</td><td></td></tr><tr><td>H4</td><td></td><td></td><td>1</td><td>1</td><td>1</td><td>1</td><td></td></tr><tr><td>H5</td><td></td><td></td><td>1</td><td>1</td><td>1</td><td>1</td><td></td></tr><tr><td>H6</td><td></td><td></td><td>1</td><td>1</td><td>1</td><td>1</td><td></td></tr><tr><td>H7</td><td></td><td></td><td>1</td><td>1</td><td>1</td><td>1</td><td></td></tr></table> <p>Coupon 1</p>		V1	V2	V3	V4	V5	V6	V7	H1								H2			1	1	1	1		H3			1	1	1	1		H4			1	1	1	1		H5			1	1	1	1		H6			1	1	1	1		H7			1	1	1	1			
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4.5.2 Comparison of the different methods

To be able to convert the increasing cycle times from the simulation and the physical trials into a percentage that is comparable to the continuity score the results for the square coupon (coupon 1) have been taken as the optimum 100% solution. The times for other components are inverted ($1 \div \text{time}$) and then divided by the time for the first coupon to generate a percentage value. The values are colour coded to highlight red as the slowest and poorest values, through to green for the fastest and most promising values in Table 15.

Table 15: Results from physical trials compared with simulation and continuity scores

	Continuity Scores	Simulated Cycle Times (Seconds)	Simulated as measure of coupon 1	Actual Cycle Times (seconds)	Actual as measure of coupon 1
Coupon 1	100%	1692	100%	1492	100%
Coupon 2	75%	2268	75%	1667	90%
Coupon 3	50%	2628	64%	1805	83%
Coupon 4	34%	3132	54%	1948	77%

The continuity scores and the simulated cycle times follow the same trend, but as complexity increases the basic continuity score and the higher fidelity process simulation both start to diverge from the actual cycle times. This can be seen in the graph of the results from Table 15, Figure 43.

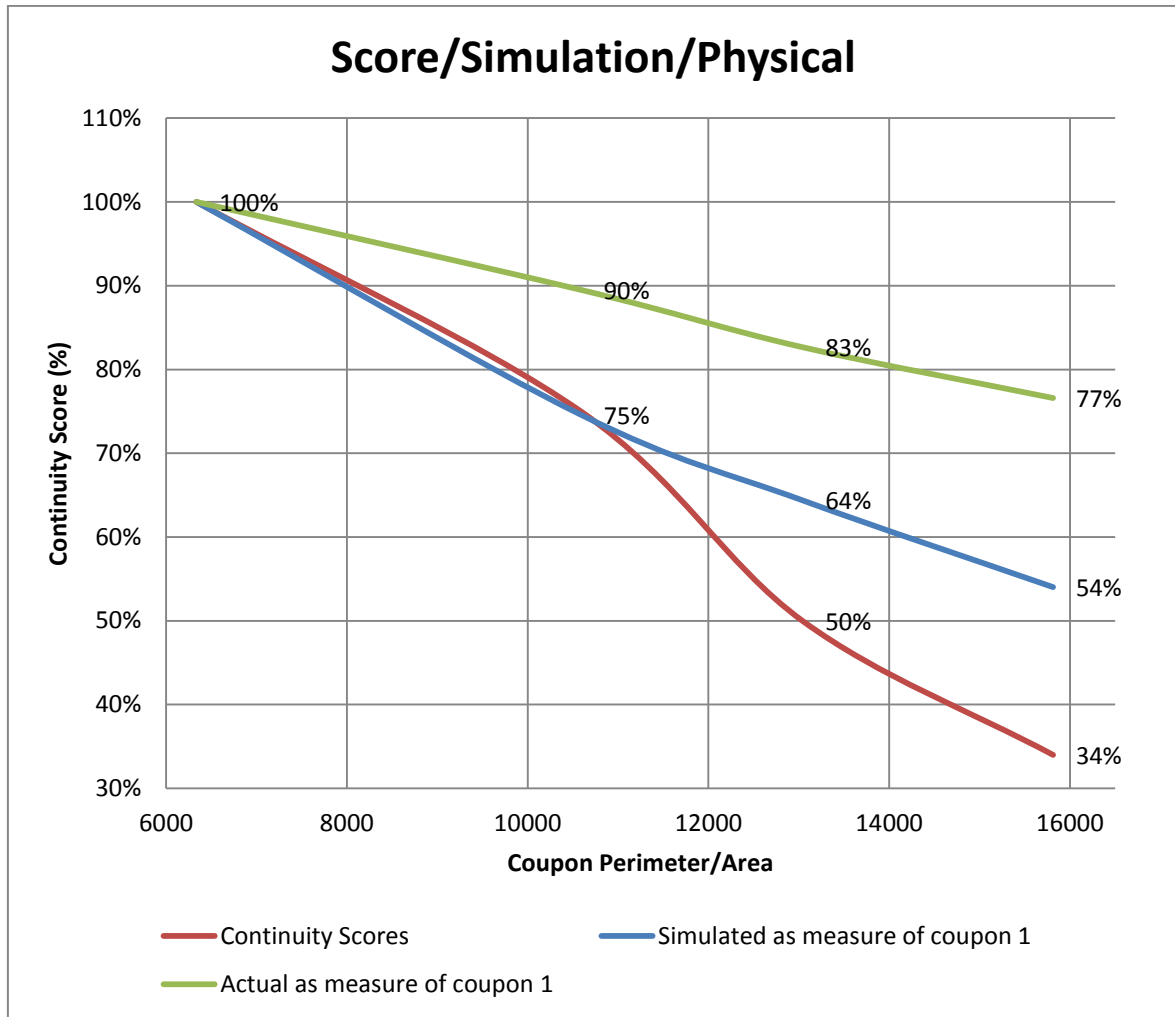


Figure 43: Graphic representation of the values from Table 15

Figure 43 shows the results displayed graphically, with coupon ply perimeter in mm displayed on the x-axis and the percentage score displayed on the y-axis. The common trend of increasing perimeter/area ratio to decreasing production cycle time can be seen.

The simulated data for the four coupons provided a smooth profile in the graph illustrated in Figure 43. The increase in coupon perimeter is not uniform for the CAD data, but the excel table is not able to capture the magnitude of the increase because it does not account for exact geometrical measurements, only an approximation of shape and scale. Whilst for both the simulation results and the continuity scores, each coupon decreases in manufacturing speed, the exact amount of decrease is not well aligned. The coupons were also smaller than ideal

for this kind of research because the flat tool available for the trials was limited to 1.2m by 1.2m in size, and the CAD models had to be reduced in scale to fit. Whilst the excel file is dimensionless and therefore unaffected by the scaling, the gaps between ply boundaries in the more complex coupons were very close together, restricting the opportunity for the AFP machine to accelerate to full speed during the simulation and physical trials.

4.6 Concluding remarks

In this chapter, three example use-cases have been used to describe how to evaluate the manufacturability of a design using automated fibre placement at three different stages in the design lifecycle. The methods to estimate manufacturability at a preliminary design stage, the simulation carried out at the detailed design stage and the physical coupons manufactured all generate the same trend of the assessment score decreasing as the ply shape complexity increases. However, the greater the complexity of the ply shapes, the more the results diverge as the simulation and ply continuity score fail to capture the full effects of complexity at their lower fidelity stages of design maturity.

To perform a simulation of the deposition process, the designer is required to create a high fidelity CAD model of the laminate, specifically defining the boundary of each ply and the orientation of the fibres. This process requires a skilled designer and takes time. For a large and complex structure like a carbon fibre aircraft wing, the design process can take over six weeks. Because the scoring methodology is able to identify the correct trend in deposition time relative to ply shape complexity, the basic laminate design can be evaluated for production speed without the need for a higher fidelity design. This enables multiple basic laminate designs to be quickly evaluated and adjusted for production potential before committing design resource to their development. Prior to this research, it was not known if the variance in each alternative design could be modelled to estimate cycle time without the presence of a detailed design. The research proves that variations in the laminate conceptual design can be evaluated during a conceptual design review using the methodologies described in section 4.2, without the need for detailed design data.

The definition of the ply shapes of the four coupons did not account for the minimum cut length required in the manufacturing process to produce 45 degree and 135 degree plies, which adds a small tab of extra material to some corners of the ply shape. A minimum cut length of 90mm was required for the AFP machine configuration used in the physical trials, but this is only applied to external corners in specific directions. When each coupon is compared, the quantity of corners that needed to be extended for minimum cut length did not uniformly increase as the complexity of each coupon increased, since each coupon had a different number of corner additions. The additional surface area and associated deposition time to manufacture these minimum cut length features impacted the cycle times of the AFP production, and whilst this is accounted for in the simulation, the scoring methodology does not identify or account for minimum cut length complexity. The study suggests that whilst not all of the complexities are represented in the continuity scoring method, it is still able to predict a valuable trend when comparing multiple design solutions, and this can be used to aid concept selection and help improve preliminary designs to ensure that DFM is applied.

5 DESIGN PROCESS AND SUPPORTING TOOLS FOR DFM

This chapter explains how a generic design process can be defined that will enable DFM to be systematically applied to composite components that will be manufactured using automated manufacturing technologies. Chapter 4 highlighted how ply continuity could be represented at an earlier stage of the design lifecycle, but also identified that another manufacturing constraint, the minimum cut length, was neglected at preliminary design, leading to divergence in the results. The systematic approach must therefore be able to identify which manufacturing constraints are significant enough to represent at an earlier design stage, and be able to sort these by relevance in order to prevent the preliminary design stage from becoming too detailed.

5.1 Introduction

The challenge of developing a strategy that enables a designer to ‘design for manufacture’ can be split into two steps. First, a designer needs a method to analyse the manufacturing potential of a design solution, and secondly, the designer needs a process which maps the analysis directly to the design intent, so that each manufacturing outcome can be linked to a design decision made earlier in the design lifecycle. This enables the designer to analyse how effectively the design can be manufactured.

Design for manufacture is widely reported in literature and in industry, albeit with few examples targeting specifically automated deposition of composites. However, the creation and use of a systematic approach is not currently described in literature.

5.2 Methods followed in this research

The methods followed in this chapter incorporate three stages. Firstly, a review of literature published in the field of design processes was required. The initial literature survey carried out in chapter 2 focused on composite manufacturing and DFM. The second stage involved testing the methods identified in the

literature survey on an automated composites manufacturing design process. The final stage was to develop use cases based on a composite component manufactured using an automated deposition process to establish if the design process could identify the relevant manufacturing constraints in a format that enabled them to be adopted into the earlier design lifecycle stages.

The majority of research carried out in the field of advanced laminates or curvilinear fibre path laminates is specific to the AFP or ATL manufacturing technology because these technologies accurately deposit composite fibres along defined fibre paths. Most other automated deposition processes such as filament winding, braiding and broad goods deposition are unable to control steered fibres to the same degree of accuracy, limiting the degree of design tailoring available. Within each AFP and ATL process there are process variables that are specific to the machine, material and environment that may be different from machine to machine and different for alternative materials, and as such, the design rules may change depending on the selection.

The reviewed research articles relating to DFM and composites focused on specific tools or specific design features but did not describe an underlying process that could be used to implement DFM. For example, in industry it is common practice to perform a failure mode, effect analysis (FMEA) on any new manufacturing process as a final check before adopting the new process. The FMEA process is generic enough to be applied to any manufacturing process, and will help to highlight any potential manufacturing failures and develop appropriate mitigations.

For composite DFM, instead of documenting the specific design and manufacturing considerations for a single machine and material, the method of identifying and negotiating conflicts between the manufacturing constraints and the design intent can be evaluated. This generic process can then be followed to identify and negotiate conflicts arising from a new material selection, or if manufacture is planned on a different machine.

In the literature review, the most relevant articles relied on process FMEA to provide the analytical structure required to evaluate the design lifecycle [98].

The method in this chapter is adapted from the commonly used Process FMEA. This approach is used to identify potential problems with a manufacturing process ahead of production at an earlier stage of the design lifecycle, and relies on user experience while following a structured analysis to attain a confident set of results. Whilst FMEA is commonly used to identify risk in a process or product, this chapter looks at adapting it to identify risk in each design step.

A standard Process FMEA consists of 5 stages:

- Capture potential failure modes
- Analyse the effects of these failure modes
- Establish root causes
- Quantify the severity
- Prioritise corrective/preventative actions

The data is typically taken from quality reports, for historic problems, and design representations for future problems. A team of assessors who have relevant subject matter experience carry out the analysis.

In order to utilise an FMEA approach to this composites design for manufacture problem the 5 steps need to be adapted to make them more suitable.

5.3 Need for systematic design process

The challenge of creating a detailed composite design is being able to resolve the conflicting requirements of the manufacturing process, and the performance requirements of the design. Each conflict arises when the design objective is different from the manufacturing objective. Whilst this makes for an interesting multi-objective optimisation problem, being able to establish what good looks like in respect to design objectives and manufacturing objectives is the reason why a requirement to follow a design process exists.

When designing in a concurrent engineering environment, different designers will be responsible for the design of different components in an assembly. If any ambiguity exists around how to satisfy conflicting requirements, and there isn't a process in place to control the decisions, then different designers can generate

different solutions in terms of performance and cost to manufacture, which is undesirable when the components are assembled into a complete system.

5.4 Design process flow

The standard process steps of an FMEA have been adapted to suit the challenge of novel composites designs:

1. Capture potential failure modes – in the context of a composite design the failure mode constitutes any design decision made upstream of manufacturing in the design lifecycle. Although a decision isn't strictly a failure, to exhaustively assess all of the process steps it is assumed that each design decision could have a negative effect on the manufacturing process, or be an opportunity to improve the manufacturing process.
2. Analyse the effects of these failure modes – in the context of composite design the effects of the failure modes either alter the design, or slow down the production speed, or exist as a combination of both.
3. Establish root causes – the root causes should identify the design decision and guidance on how the decision could affect the manufacturing process.
4. Quantify the severity – Any conflict between 'good for design performance' and 'good for manufacture performance' should be ranked for severity.
5. Prioritise corrective/preventative actions – Guidance should consider the severity, so outcomes rating high in one discipline and low in the other default to the recommended outcome, and situations where severity is equal between design and manufacture, adequate information is provided to help an engineer make an informed decision.

The FMEA approach was systematically applied to all of the design steps from concept to detailed design for the AFP process to create a design process. The process flow is recorded in section 5.4.1 through to section 5.4.4. The resulting process contained 28 steps which is defined in section 5.4.5. The effects, root causes, severity and corrective actions were all recorded in greater detail in Appendix A.

The experts who were part of the FMEA assessment panel are described in Table 16.

Table 16: Experts used for FMEA process

Expert ID	Area of expertise	Location	Years of experience
Expert 1	AFP Manufacturing Optimisation	Industry: Aerospace & Defence	13
Expert 2	Detailed design of composite structures & AFP Machine programming	Industry: Aerospace & Defence	17
Expert 3	Preliminary and detailed design of composite structures	Industry: Aerospace	13

The design process flow is summarised as a generic design process to suit automated composites manufacturing technologies in sections 5.4.1 to 5.4.4. The design process is described in higher fidelity in section 5.4.5 with an physical part used as an example for the specific dry fibre AFP process. This is illustrated in Figure 44.

5.4.1 Process for conceptual design

The conceptual design phase for a composite component starts with a low fidelity CAD surface, typically with no thickness data available for it, but sufficient fidelity to show the overall shape of the composite structure. In the aerospace industry, this CAD data is usually the aerodynamic surface for the composite structure.

The first practice identified by the experts listed in Table 16 was the surface offset check and the ply boundary check. These serve as early indicators of the suitability of the CAD surface. Since all composite layers that will be digitally built onto this surface will need to be offset by a ply thickness, and be constrained with a perimeter boundary, these checks highlight any low quality CAD and prompt it to be repaired prior to progressing the design. This process loop is illustrated in the upper section of the process flow in Figure 45.

Once the input CAD surface has been checked and passed, the rosette definition must be checked. The rosette determines how the designed fibre orientations will be interpreted, and consists of a vector for each listed ply orientation, positioned around a single point positioned on the CAD surface. The experts described the practice of extending the fibre orientation vectors from the rosette and maintaining a trajectory that is normal to the surface. This is known as a geodesic trajectory in design terms. The trajectories are expected to deviate from a straight course if the surface exhibits geometric complexities such as tapers, joggles and ramps, however the severity of the deviation is related to the starting position of the rosette. If the rosette check highlights that the trajectories are deviating by more than the allowable angle, then the rosette must be re-positioned. In the aerospace industry, the allowable angle is typically 3 degrees.

If all of these checks are passed, the design can progress into the structural sizing stage of its lifecycle.

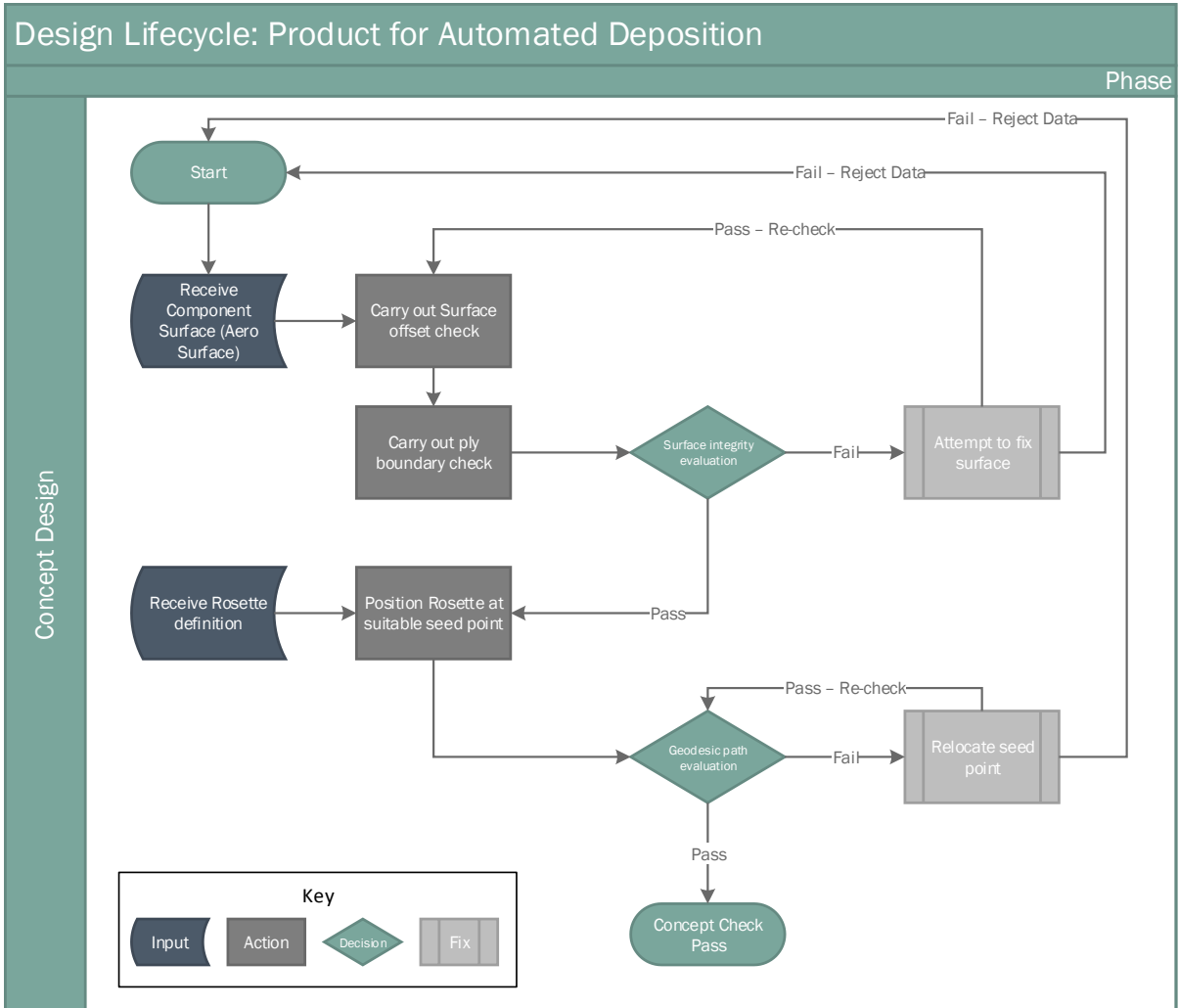


Figure 45: Process flow for the conceptual design stage of the design lifecycle

5.4.2 Process for structural sizing

The structural sizing process begins after the conceptual design checks have been completed. The process takes the initial input design data and increases the design fidelity to include realistic material thickness distributions.

The first action is to convert the sizing data to thickness laws, and then convert these into higher fidelity stacking sequences. Once the stacking sequences are generated, then they can be evaluated for ply continuity. The stacking sequences are also combined with the 2D array to create a composite ply definition model.

The ply continuity evaluation enables the concept to be evaluated for manufacturability, and gives the designer the opportunity to revise the stacking sequence to improve the ply continuity score before progressing to the generation of ply shapes.

After the manufacturing ply shapes have been generated, a comprehensive set of manufacturing scores such as ply continuity and ply complexity can be generated. By combining the composite ply definition with the 3D CAD surfaces, the 2D sizing data can be represented as a 3D CAD model and a preliminary evaluation of manufacturability can be carried out.

If the manufacturability evaluation generates an unacceptable score, then the process loops back to the thickness laws to request changes to further improve ply continuity. This is illustrated in Figure 46.

If the manufacturing evaluation is acceptable, then the design can progress to the detailed design stage of the design lifecycle.

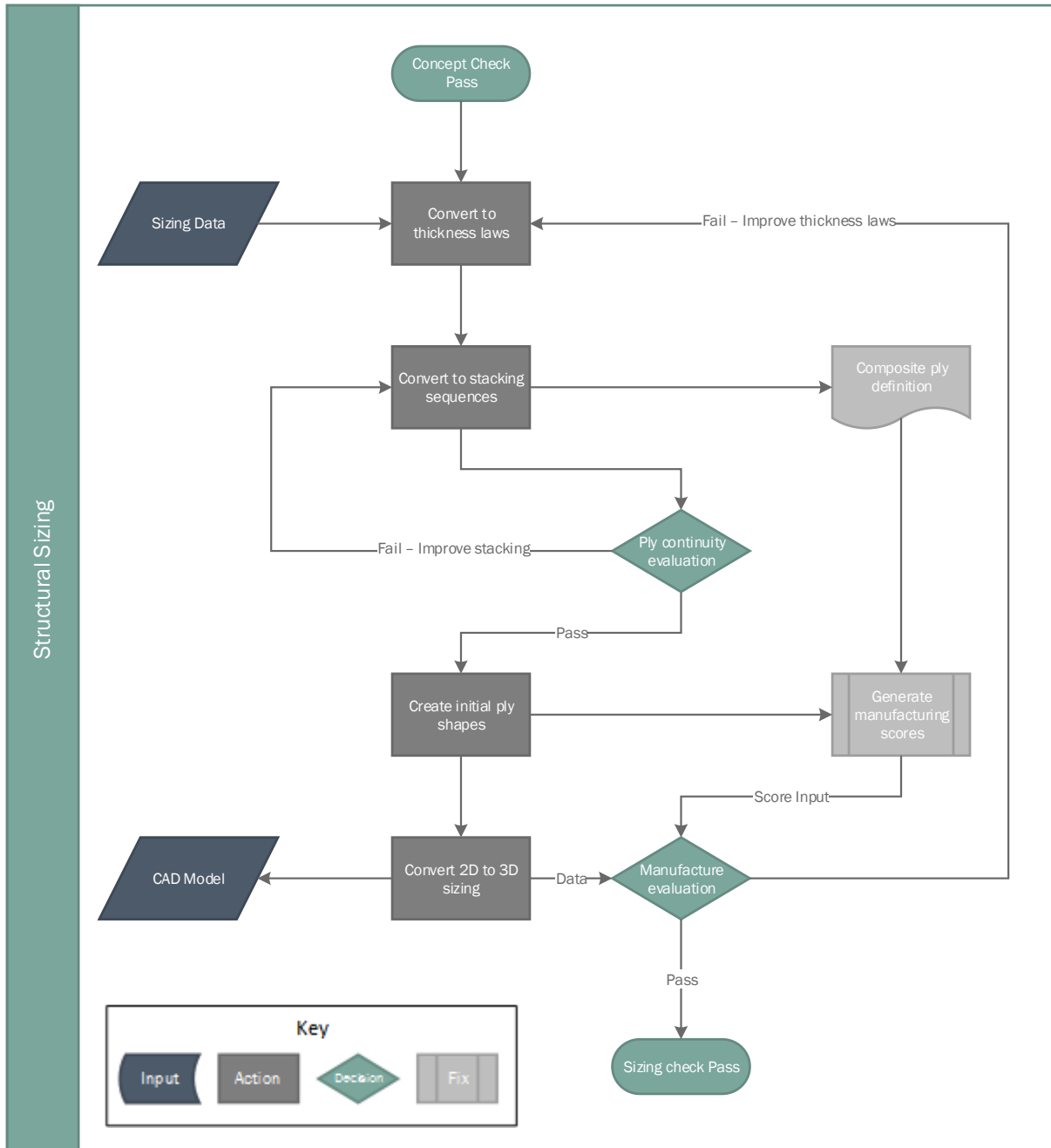


Figure 46: Process flow for the structural sizing stage of the design lifecycle

5.4.3 Process for detailed design

The detailed design stage starts with a structurally sized component which has passed the manufacturing evaluation check in the structural sizing (preliminary design) stage of the design lifecycle.

The first design step is to configure the ramps and clearances required to accommodate changes in thicknesses. If the rate of change of thickness between neighbouring cells is too great, the selected deposition machine may not be able to access the geometry and the ramp rates will need to be reduced, which causes mass to increase.

If the ramp check is passed, then the ply definition model and laminate attributes can be added to the 3D model to further improve the design fidelity. At this stage, the individual ply layers in the structure can be visualised in 3D, and a more accurate ply shape assessment can be made.

If the ply shape assessment results in a poor score, the stacking sequences will require re-sequencing to improve ply continuity. If the ply shape assessment results in an acceptable score, the CAD tool can be used to generate high fidelity ply boundaries. When these high fidelity ply boundaries are assessed, any failures are entirely attributable to the 3D surface and not the sizing data, so the failed design must regress back to the conceptual design stage so that the 3D surface can be improved. If the ply shape assessment results in a pass, then the design can progress to the DFM stage of the design lifecycle. This is illustrated in Figure 47.

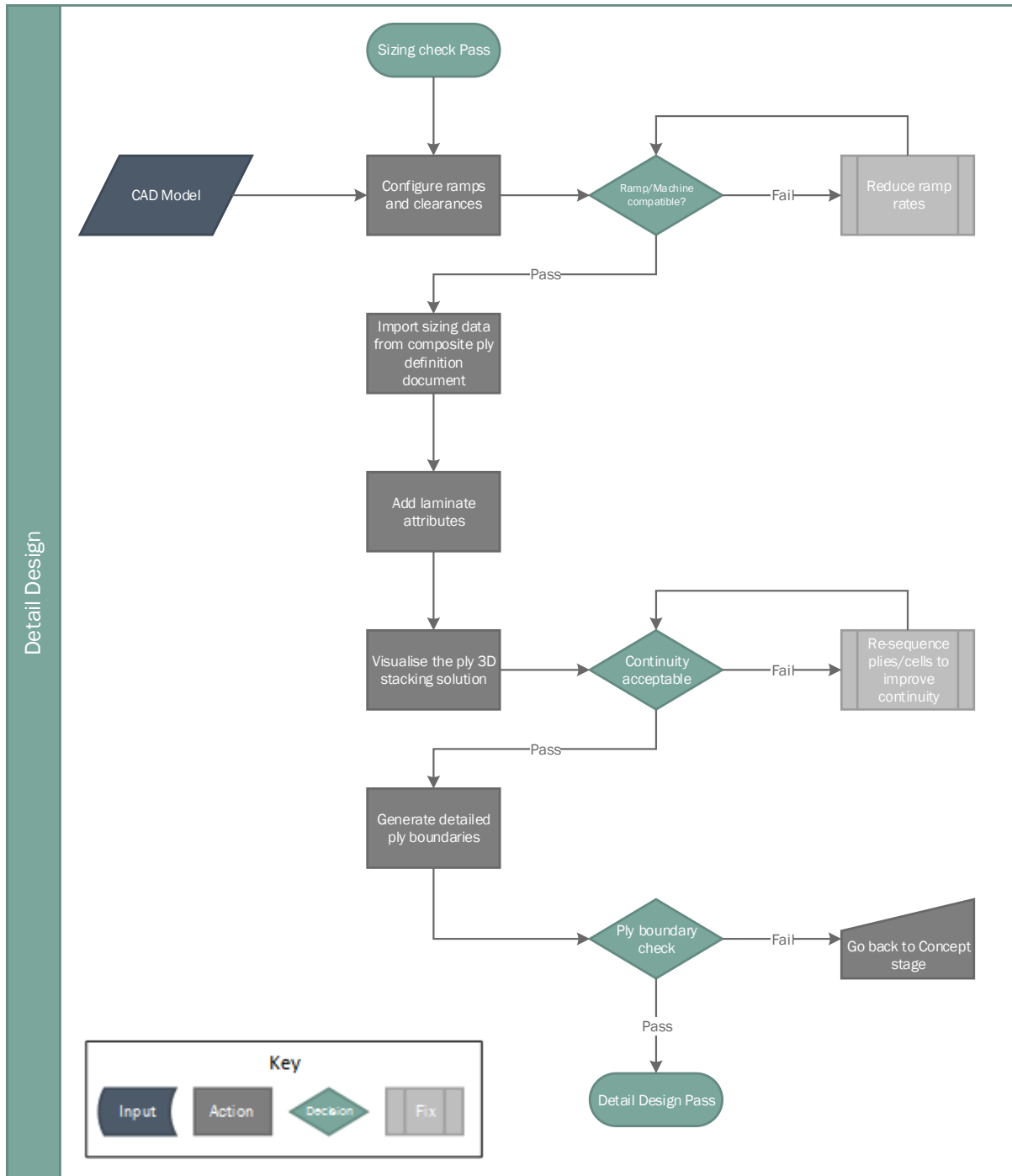


Figure 47: Process flow for the detailed design stage of the design lifecycle

5.4.4 Process for DFM

The process for DFM begins with a completed detail design. The first design step is to define the deposition strategy, as this establishes the manufacturing constraints that will form the basis of the DFM activities carried out in this phase

of the design lifecycle. This information includes key characteristics such as the minimum cut length for the selected machine, the dimensions of the deposition roller and the motion performance values for the deposition system.

With the manufacturing system data now known, the ply boundaries can be revised to accommodate the machine specific manufacturing constraints such as minimum cut lengths. There are multiple different ways to account for minimum cut lengths, so a ply boundary assessment loop is used to check and adapt the ply boundaries. This is illustrated in Figure 48.

The next step of the design process is focused on the generation of geodesic guide curves which form the guide for fibre trajectories deposited by the deposition machine. The guide curves are created using the rosette, and whilst the guide curves can be steered, they must remain geodesic (normal to the surface) around any complex geometry such as corners or ramps. The designer must steer the guide curves to enable geodesic compliance around the complex features, but without exceeding the steering or angular deviation limits set by the deposition strategy. To enforce this, the process introduces assessment and adaption loops for geodesic, steering and angular deviation checks. This is illustrated in Figure 48.

The next step is to generate ply coverage by defining where each strip of material will be deposited. The trajectories can converge or diverge, and their positioning on the surface relative to each other will cause either gaps or overlaps in the ply coverage. The gap and overlap limits are defined in the deposition strategy, so the process introduces three different gap checks for course to course gaps, tape to tape gaps and overlaps. If any fail to meet the criteria of the deposition strategy, the guide curves must be adapted and regenerated.

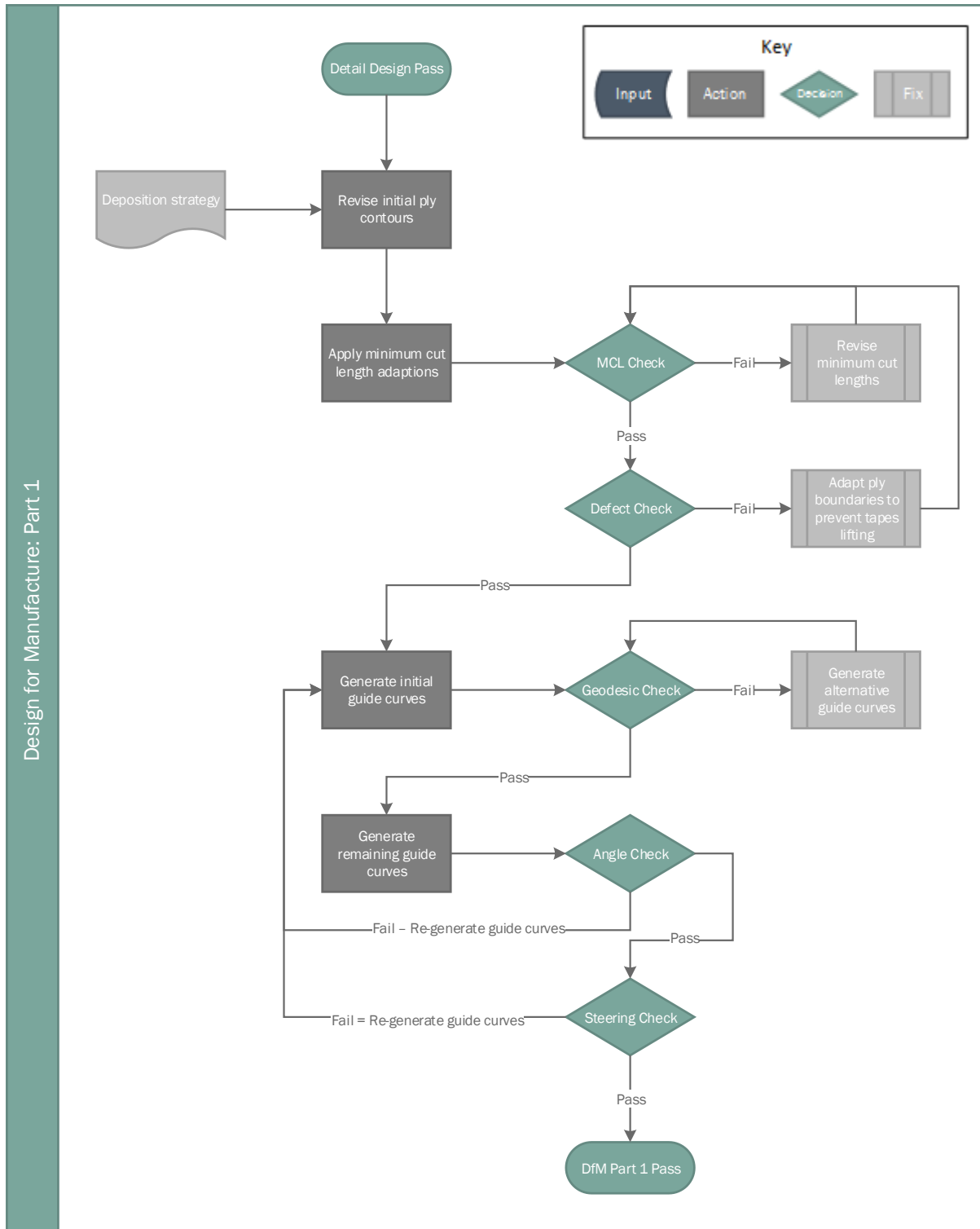


Figure 48: Process flow for the first part of the DfM stage of the design lifecycle

The laminate quality requirements are used to establish the constraints for the ply stagger and convergence strategy. The ply stagger ensures that the gaps in the laminate do not align out of plane when more plies are deposited on top of

existing plies. The convergence strategy is required for joining two adjacent plies which are not parallel to each other.

Any areas which may become highly consolidated during the deposition process need to be identified at this point, as the designer can introduce gaps to aid with resin flow in these areas. The process introduces a check for consolidation which triggers a loop to improve the amount of gaps locally where high consolidation is anticipated. This is illustrated in Figure 49.

The next design step is to generate the geometry required to support the deposition strategy. Each ply requires a unique guiding geometry set since reusing the trajectories from a previous ply would cause the gaps and overlaps to align and therefore fail to meet staggering requirements. Once guiding geometries have been defined, all of the ply coverage in the laminate can be generated. If the ply coverage fails to generate, the guiding geometry needs to be revised.

The final design step is to simulate the deposition process. The simulation checks that the deposition machine can access the component and tooling adequately. If the tool cannot be accessed then it can be re-positioned in the deposition cell and re-simulated. This loop is illustrated in Figure 49.

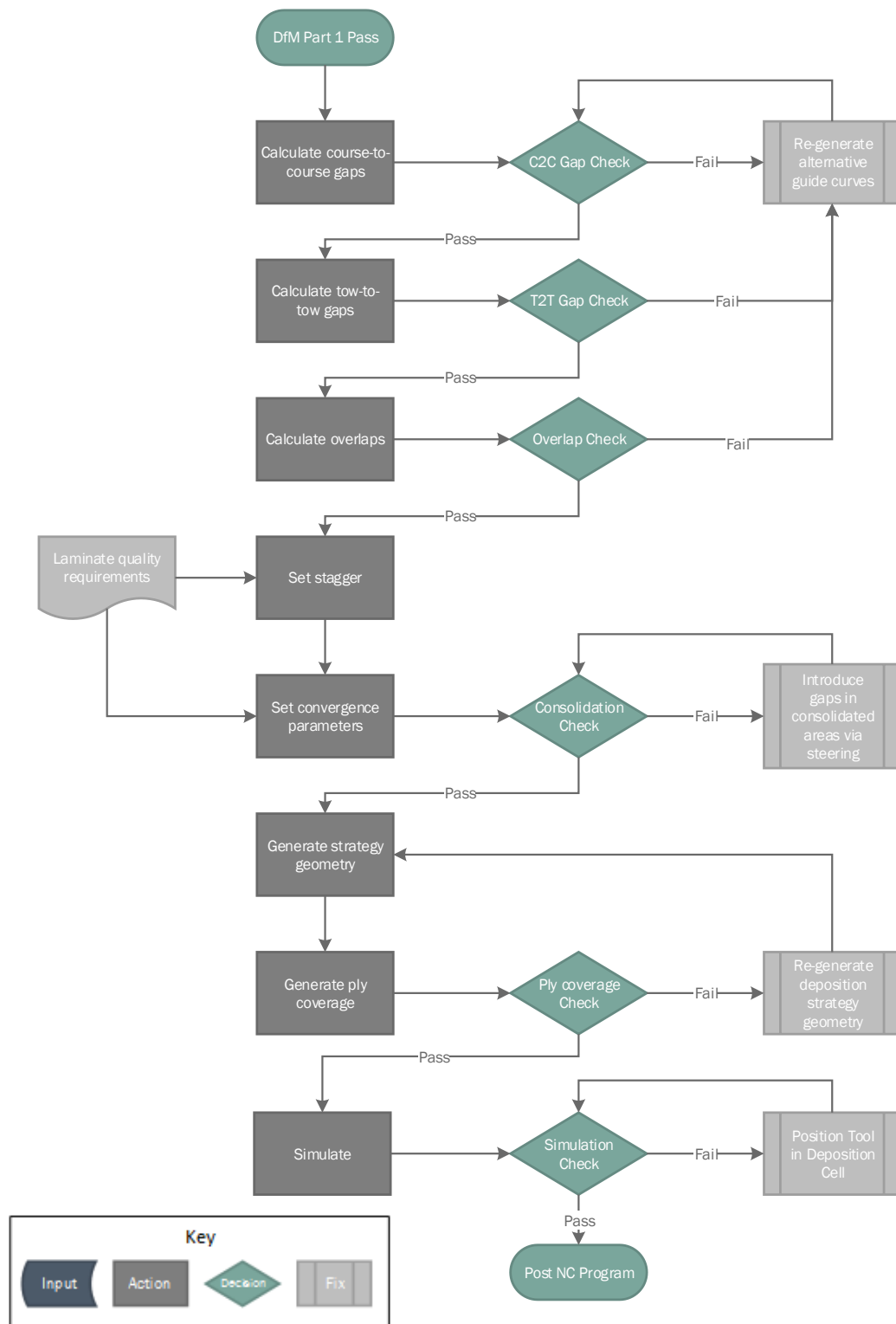


Figure 49: Process flow for the second part of the DFM stage of the design lifecycle

5.4.5 Overall FMEA process

The process flow described in section 5.4.1 to section 5.4.4 was assessed using the adapted FMEA approach described in section 5.3. The detailed results are provided in Table 17, Table 19, Table 19 and table 20. Three of these design steps have been described in full detail in section 5.5.

Table 17: FMEA for the first 7 design steps

Process Step	Design Phase	Task Objective	Task Description	Severity	Design Objective	Manufacturing Objective	Failure Mode	Effects of Failure	Root Cause	Corrective Action
1	Concept	Check integrity of surface	Offset surface by 0.2mm	High	Successfully test surface integrity	Prove ply offsets will work in downstream	Surface fails to offset	Design cannot be progressed without surface	Surface continuity inadequate, typically as a result of generating surfaces from CFD data	Return surface, do not proceed
2	Concept	Check integrity of surface	Apply extended ply boundary	High	Successfully test surface integrity	Check that surface doesn't have unplanned holes or	More than one boundary generated	Design cannot be progressed without surface repairs	Surface broken into multiple segments	Fill surface, otherwise return and do not proceed. Extend surface by at least 200mm tangentially
3	Concept	Position rosette on surface at suitable seed point	Install rosette in model. Geodesic extend each orientation to edge of surface	High	Ensure 0 degree and 45 degree axis are correctly orientated	See how far the fibre angle deviates when geodesically extended	Location of rosette and seed point cause geodesic fibre deviation that exceeds specified limits	Unable to deposit fibres on surface without introducing unacceptable defects	Geodesic fibre paths form the ideal defect free trajectories, but are diverted by complex geometries. If the seed point is poorly located, multiple complex geometries cause compounded deviations.	If deviation too great, consider alternative seed point to locate rosette if possible, otherwise return and do not proceed
4	Sizing	Establish ply sequences	Calculate ply sequence for each sized zone based on thickness law and thickness	Low	Convert Thickness Law and thickness into a balanced stacking sequence (Minimum thickness)	Ensure manufacturing ply sequence rules are applied (results in added thickness)	More than 3 layers of the same orientation are sequenced together	Ply interlock and cause bridging or wrinkling upon material de-bulking	Ply with same orientation interlock and prevent inter-ply shear during cure or de-bulk	Add plies (thickness) to satisfy manufacturing constraints
							45 and 135 or 0 and 90 degree plies are not equal	Laminate warps during cure	Un-balanced laminates cause residual stress. At least two perpendicular orientations should be balanced	Add plies (thickness) to satisfy manufacturing constraints
5	Sizing	Evaluate ply shapes	Transpose stacking sequences into individual ply shape maps	High	Create basic laminate definition to show which plies within a zone are continuous to neighbouring zones	Increase ply continuity	Ply continuity score unacceptable	Sub-optimal manufacturing solution	Excessive tailoring of the stacking sequences leads to poor ply continuity, as a result the deposition process is slowed down	Re-sequence with alternative stacking sequences until ply continuity is improved. If stacking sequences have been provided instead of thickness laws, change sequence by maximum of 10% of
6	Sizing	Generate sizing evaluation score	Calculate the perimeter/area score for all ply shapes	Low	Higher score indicates greater degree of continuous fibres in the	Higher score indicates faster manufacturing process	Ply continuity score unacceptable	Sub-optimal manufacturing solution	Excessive tailoring of the stacking sequences leads to poor ply continuity, as a result the deposition process is slowed down	Consider engineering stacking sequences to influence higher score
7	Sizing	Convert 2D sizing to 3D sizing	Map sizing data onto surface - establish grid in eCPD	Low	Grid must closely match zone defining features of the sizing data	Zone boundaries should be clearly defined, preferably using intersecting simple geometry like planes	Grid construction not suitable for propagating ply boundary support guides	Without supports the ply boundaries cannot be generated	Sub-standard geometry used to configure composites grid elements. For example, planes can easily be offset to create a staggered ply boundary, but complex geometry can sometimes not be offset using geodesic or euclidean functions	Grid integrity will not be tested until ply boundaries are generated later in the design process
							Grid contains different number of cells to input	Ply definition does not load correctly	Transposition of 2D array to 3D grid does not match	

Table 18: FMEA for design steps 8 to 15

Process Step	Design Phase	Task Objective	Task Description	Severity	Design Objective	Manufacturing Objective	Failure Mode	Effects of Failure	Root Cause	Corrective Action
8	Detail Design	Configure ramps and clearance parameters	set ply boundary rules (ramping rates)	High	Set exclusion zones where ramping should not occur - such as in interface areas	Restrict ramping rates as the angular changes cause changes in fibre direction and can	Ramp geometry too steep for deposition roller access	Deposition machine cannot access ramped areas	Angle of ramp causes roller to bridge preventing adequate consolidation of material	Change clearance zone and ramp rates and re-compute
							Ply boundaries too close together	Deposition slowed excessively to perform boundary cuts and starts	Ply boundaries are sufficiently spaced in the grid until the ramping rules move them	
							Ply shapes fragmented	Sub-optimal manufacturing solution	Excessive tailoring of the stacking sequences leads to poor ply continuity, as a result the deposition process is slowed down	
9	Detail Design	Add laminate attributes to model	Import/enter sizing data into the grid definition within eCPD	Low	Represent sizing data with minimal changes	Ply coverage should be as continuous as possible	Uncured ply thickness not representative	Deposition NC program causes either poor consolidation or collisions	The deposition program requires a revised surface to follow at 2mm layers in the laminate. If the revised surfaces are too low relative to the programmed surface the roller does not consolidate the laminate, too high and the machine may collide with the laminate.	Re-check grid definition if import is not successful
							Orientation nomenclature incorrect	Ply orientations transposed incorrectly	CAD material catalogue doesn't match sizing data material	
10	Detail Design	Explode the laminate to illustrate individual ply coverage	Visualise the initial stacking sequence by plies	Low	Move non-connected plies to different layers in the laminate where they improve continuity & move non-symmetry to centre of laminate	Fill gaps in the plies by moving material through the stacking sequence, strive for maximum symmetry, better ply continuity	Sizing transposition incorrect	Sub-optimal manufacturing solution	Excessive tailoring of the stacking sequences leads to poor ply continuity, as a result the deposition process is slowed down	Pass design back to sizing if a symmetrical laminate cannot be achieved
11	Detail Design	Outline initial ply contours	Automatically generate ply boundaries	High	Establish how clearance and ramp rates affect ply boundaries	Join small gaps in plies that have arisen from boundary conditions	Ply boundaries too close together	Deposition slowed excessively to perform boundary cuts and starts	Ply boundaries are sufficiently spaced in the grid until the ramping rules move them	If plies do not generate add ramp support fallback conditions, then re-check grid definition for complex
							Unacceptable ply interleaving	Poor interleaving in a ramp can cause delamination	Incorrect settings used for automatic ply generation	
12	DfM	Revise initial ply contours	Regenerate ply boundaries after stacking data has been updated	Medium	Capture any modifications to the stacking needed due to ply boundary issues	Join small gaps in plies that have arisen from boundary conditions	Ply boundaries too close together	Deposition slowed excessively to perform boundary cuts and starts	Ply boundaries are sufficiently spaced in the grid until the ramping rules move them	If plies do not generate add ramp support fallback conditions, then re-check grid definition for complex geometry
13	DfM	Account for minimum cut length	Check minimum cut length for all ply boundaries	High	Add material and re-shape areas of the ply boundaries that cannot be laid due to minimum	Ensure features that cannot be laid are removed	Minimum cut length not achieved	Unable to deposit fibres in key areas	Minimum cut length is required to feed material onto laminate. If the design requires shorter fibres, they cannot be deposited	If angle cut wizard fails, manually add minimum cut length allowance to all affected ply boundaries
14	DfM	Account for short fibres	Check any areas where short fibres might delaminate due to spring forces	Medium	Ensure additions are added to detail design model, particularly if they are inside the trim allowance	Short tapes over radii may spring off the laminate and need to be extended, sometimes this is not	Short fibres not added in areas where tapes are in tension	Fibres lift off laminate after deposition	The material's natural spring overcomes the adhesion over a short length. Extending the length increases adhesion	Liaise with design - it may not be able to add extensions without changing internal surface definitions and interfaces
15	DfM	Initiate guide curves	Generate at least one guide curve per ply to base the machine trajectory on	High	Make guide curve angle as close to the design rosette for that ply	Follow a geodesic path to reduce defects in the deposited material - although this may invoke steering to	Geodesic path exceeds material steering limit	Material is deposited with defects	When steering radius is exceeded the material buckles and lifts from the laminate causing a defect	Feed fibre angular deviation and steering values back to design so the stress model can be re-validated. In most cases, the design intent cannot be manufactured.

Table 19: FMEA for design steps 16 to 22

Process Step	Design Phase	Task Objective	Task Description	Severity	Design Objective	Manufacturing Objective	Failure Mode	Effects of Failure	Root Cause	Corrective Action
16	DfM	Generate trajectories	Apply a deposition strategy to create the tape courses for each ply	High	Fill in the ply boundary with UD material	Generate coverage with acceptable gaps, overlaps, steering and angular deviations	Trajectories diverge	Fibres part leaving a gap, sometimes needing to be filled with an infill strip and convergence zones	Complex features cause geodesic fibre paths to be diverted	Failure to generate adequate coverage will need a convergence zone adding, a new ply boundary or a new geometrical surface - liaise directly with design.
							Trajectories converge	Fibres overlap or have to be terminated in a convergence zone	Complex features cause geodesic fibre paths to be diverted	
17	DfM	Governance: Fibre angles	Check angular deviation	Low	Try to maintain transposed angles from the rosette	Steer to maintain geodesic path to reduce tape defects	Fibre angles exceed allowable tolerance	Laminate has incorrect structural properties	Fibre trajectories diverge by angle greater than allowed	If fibre angle deviates too much from design intent revisit geometry with designer to reduce geodesic impact
18	DfM	Governance: Steering Radius	Check radius of steering	High	Try to maintain transposed angles from the rosette	Steer fibre trajectories back to recover angular deviation caused by geodesic effects, but do not exceed minimum radius	Material steering limit exceeded	Material is deposited with defects	When steering radius is exceeded the material buckles and lifts from the laminate causing a defect	If minimum radius exceeded, change starting and ending fibre alignments to reduce the degree of steering required
							Fibre angles exceed allowable tolerance	Laminate has incorrect structural properties	Fibre trajectories diverge by angle greater than allowed	
19	DfM	Governance: Course Gaps	Check course to course gaps	High	Try to keep individual gaps below 2mm, while not exceeding a cumulative gap width of 25mm in a 1m width of ply coverage	Distribute gaps to assist with steering	Cumulative gap width limit exceeded	Laminate weakened with potential for fibre volume fraction to be reduced	To cope with double curvature geometry, hybrid steering introduces gaps to recover fibre angles	Liaise with design or reduce course width by dropping tows
							Individual gap width limit exceeded	Laminate weakened with potential for fibre volume fraction to be reduced	Course to course gap combined with steering causes excessive gaps	
20	DfM	Governance: Tow Gaps	Check tow to tow gaps	High	Reduce gaps where possible	Ensure individual and cumulative gap widths do not exceed design conditions	Tow to tow gaps exceed limit	Laminate weakened with potential for fibre volume fraction to be reduced	Course to course gap combined with steering causes excessive gaps	Re-evaluate number of tows deposited and degree of steering if gaps are excessive
21	DfM	Governance: Overlaps	Check overlaps	High	Reduce overlap to design limits or lower	Try to avoid overlaps at all costs	Overlaps exceed design limits	Excess material thickness build up creates surface defects	Incorrect strategy for gaps and overlaps	Overlaps will cause an increase in thickness and should be avoided if possible, if not - highlight impact on top surface to design
22	DfM	Prevent alignment of gaps through laminate	Set stagger	High	Move the starting seed point of each ply so that they do not line up through the laminate	Set seed point as close to centre of largest geometrical feature, stagger from seed point	Gaps or overlaps align through the z axis of the laminate	Laminate weakened with potential for fibre volume fraction to be reduced	Course to course gap combined with steering causes excessive gaps	Reiterate generation of coverage with new seed and stagger points until coverage is acceptable

Table 20: FMEA for design steps 23 to 28

Process Step	Design Phase	Task Objective	Task Description	Severity	Design Objective	Manufacturing Objective	Failure Mode	Effects of Failure	Root Cause	Corrective Action
23	DfM	Establish convergence strategies	Set boundary and convergence parameters	High	Transition ply coverage using original rosette where possible	Sectorise the ply coverage to allow acceptable convergence zones	Fibre angles across component deviate from original rosette by more than the design	Laminate has incorrect structural properties	Fibre trajectories diverge by angle greater than allowed	Liaise with design about acceptable convergence strategies
24	DfM	Identify areas of high consolidation (dry fibre)	Highlight the areas in a structure where poor permeability is likely to occur	High	Maintain target fibre angles and a fibre volume fraction within design limits	Steer to introduce gaps in and around areas of high consolidation to allow resin to flow in areas of poor	Geometrical features over-consolidated	For dry-fibre preforms, the feature permeability is too great to enable resin infusion and the component cannot be	The fibres are over-compacted leaving insufficient air content, or permeability for the resin to flow through the preform.	Poor permeability could cause a dry infusion, therefore more radical mitigations may be required in discussion with design
25	DfM	Create custom guide curves	Create curves for steering and sectorisation if	High	Align angle of curves to fibre angles in sizing	Control steering and gaps using a design controlled geometry	Generated trajectories do not match fibre angles in sizing within	Laminate has incorrect structural properties	Fibre trajectories diverge by angle greater than allowed	Liaise with design if guide curves exceed angular deviation limits to have geometry changed accordingly
26	DfM	Generate tape coverage	Build ply coverage using guide curves for sectorisation and guides for each ply	Low	None	Generate coverage with acceptable gaps, overlaps, steering and angular deviations				Reiterate with different coverage parameters
27	DfM	Check tape coverage in simulation	Simulate the deposition of the tapes, adjusting for machine reach and component location	High	None	Check geometry and positioning of component is acceptable for AFP machine access	Geometry prevents access of AFP head	Material is deposited with defects (bridging) or the machine collides with laminate	Deposition machine cannot access the deposition surface	Re-position component in AFP cell or liaise with design to change geometry
28	DfM	Calibrate tool location	Probe the location of the physical tool and re-run simulation	Medium	None	Position tool and re-check program as the reach of the machine will be slightly different from	AFP machine cannot reach component when positioned in real world	When tool is positioned and program updated to account for real world environment, machine cannot reach/access	Offline program assumes ideal position of tool. It is possible to position tool outside of machine reach for components close to the limits of the machine envelope	Physically reposition tool or change programming parameters for machine deposition strategy

5.5 Overview of design step examples

In order to highlight how this process can be adapted to work with the design lifecycle, three example use-cases that have been taken from the overall process are described in detail to provide three examples. The first addresses the effects of minimum cut length, previously identified as having a negative impact on manufacturing evaluation methods in section 4.6. The second example highlights the problems associated with short fibres and the design modifications required to eliminate manufacturing defects. The third example describes the effects of high deposition forces on the laminate, and how the design can be altered to compensate areas of the laminate which exhibit poor material permeability from locally high consolidation forces.

These three examples were selected because they each provide a demonstration of design evolution which can be quantified with a change in component mass, a reduction in process speed and a potential failure to be manufactured.

5.6 Design step for minimum cut length (first example)

In the minimum cut length design step, the panel agreed that the design objective and manufacturing objective are complementary and well-understood. The design step relates to step 13 from the overall design process. The manufacturing constraints can be easily described and quantified, and therefore the manufacturing best practice can be accurately applied at an early stage of the design, and in some cases, fully automated.

The minimum cut length is a parameter that is specific to each type of material deposition machine. In the case of the Coriolis AFP machine that is most commonly used at the NCC, the minimum cut length value is 100mm.

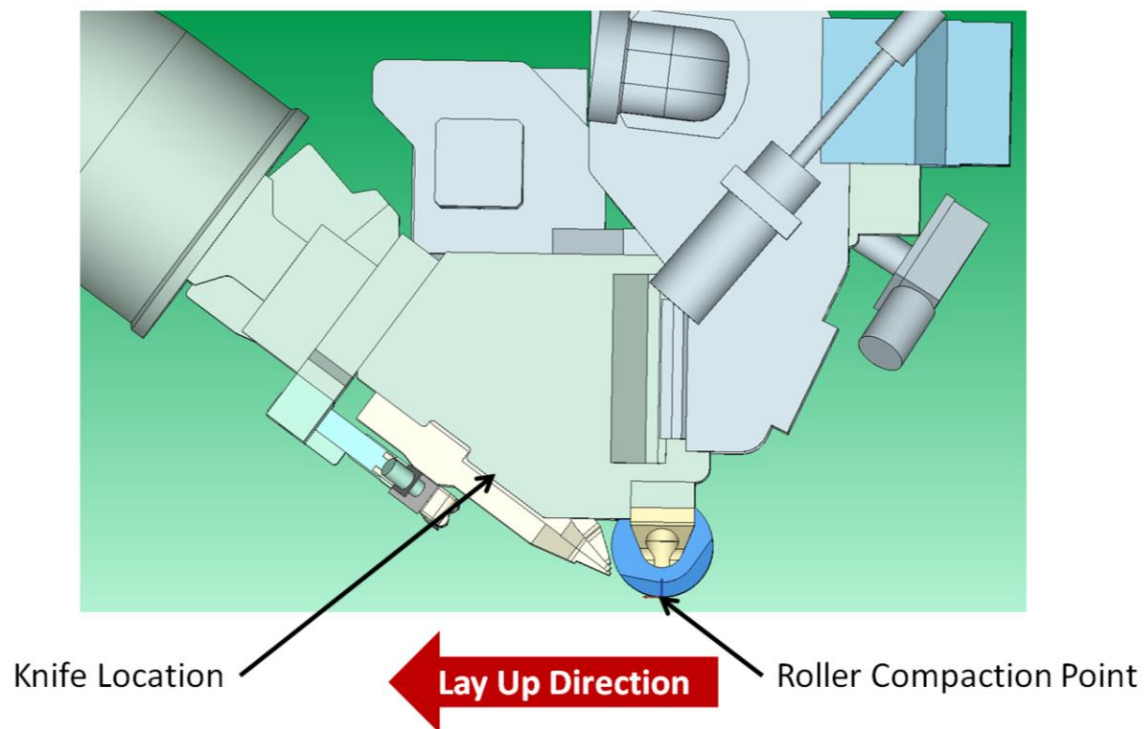


Figure 50: Schematic of the Coriolis AFP machine deposition head

The 100mm represents the length of material between the location of the knife which cuts the material, and the point where the deposition roller clamps the material against the tool or laminate. This is illustrated in Figure 50. If the AFP machine attempts to deposit a length of material shorter than the minimum cut length, then the material falls out of the AFP head before the roller can position it onto the tool or laminate.

The impact on the design is seen in two kinds of feature: general plies that are smaller than the minimum cut length and the corners of diagonal plies, which have to be extended as in Figure 51.

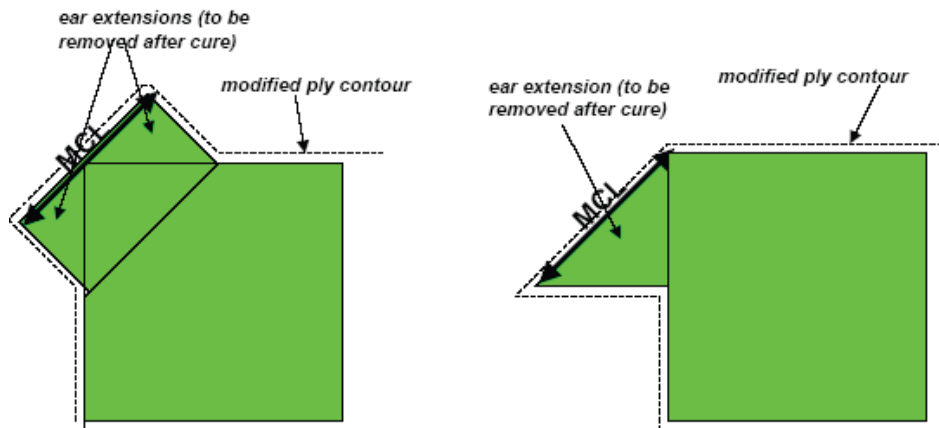


Figure 51: Examples of minimum cut length additions to diagonal plies

5.6.1 Minimum cut length design objective

The design objective for minimum cut lengths is to add material and re-shape areas of the ply boundaries that cannot be laid due to the minimum course length.

It is important for the designer to account for the effects of minimum cut length in the initial design because it can significantly change the shape of key design features. In a constant thickness laminate, the designer may need to create a hole, and subsequently add a few additional plies of material around the hole to account for the non-continuous fibres cause by the hole. The most mass-efficient shape for these extra plies is a circle, but Figure 52 illustrates how this shape can change to an octagon when the minimum cut length constraint is applied.

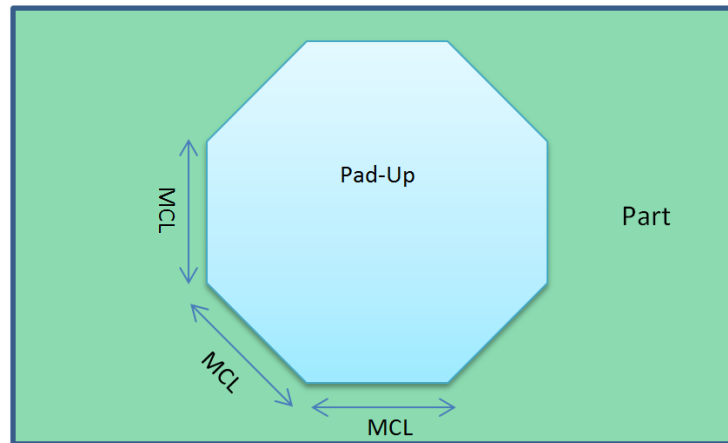


Figure 52: An internal pad-up (locally thicker area) changes shape to an octagon due to MCL

5.6.2 Minimum cut length manufacturing objective

The manufacturing objective is to ensure that the features that cannot be laid are removed or corrected.

In order to manufacture the design, there must be no tapes of material that are shorter than the minimum cut length. There are often multiple resolutions for fixing tapes that are shorter than the minimum cut length, and the lowest mass solution is typically the preferred option where component performance is important, or the solution with the fewest tape-cuts if production speed is more important.

5.6.3 Minimum cut length analysis

Failure Mode: Minimum cut length not achieved – cannot manufacture using automation

Effect(s) of Failure: Unable to deposit fibres in key areas – fibre drops out of head of machine. Machine may need to be stopped so a manual operation can be introduced.

Root Cause: Minimum cut length is required to feed material onto laminate. If the design requires shorter fibres, they cannot be deposited using automation. They may be able to be hand-deposited but at a severe productivity disadvantage, and with lower accuracy and repeatability compared to automated deposition.

Design Severity: High – Designs which are not 100% automatable require operator interaction which severely affects productivity. Accuracy of the hand-laminated plies is not as high as with automation, so the design allowable or safety factor of the design may need to be increased.

Manufacturing Severity: High – Manual operator interaction is highly undesirable. Some deposition machines use high powered lasers for heating, so the process for stopping the machine and making the work area safe to enter for a laminator will add significant delay to the process.

Corrective Action: If the design is checked and found to have short fibres, manually add minimum cut length allowance to all affected ply boundaries. In CATIA V5 R21 and higher, the checking process and suggestion of potential solutions is now automated, so the designer only needs to be able to choose the best solution for the design intent.

5.6.4 Example minimum cut length panel

The minimum cut length becomes significant when a designer creates a simple quasi-isotropic composite laminate and is required to introduce a Ø50mm diameter hole in the centre. In order to account for the broken fibres caused by the hole, the thickness of the panel is locally increased around the hole by 20% for a minimum distance of 50mm.

Figure 53 illustrates the flat panel with a reinforced circular pad-up around the hole. If the component was laminated by hand, this solution would have the lowest mass and be easily achievable using a manual process.

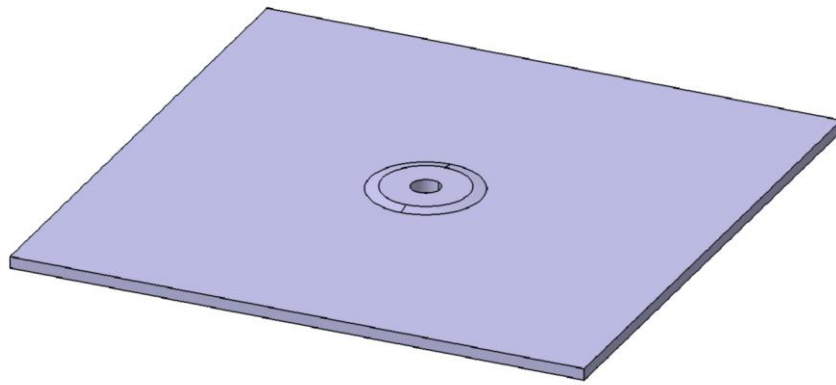


Figure 53: Hole in fat panel - hand-layup solution

If the same component is manufactured using a Coriolis AFP machine with a minimum cut length of 100mm, then the design must be modified to account for the machine restrictions. This solution is shown in Figure 54.

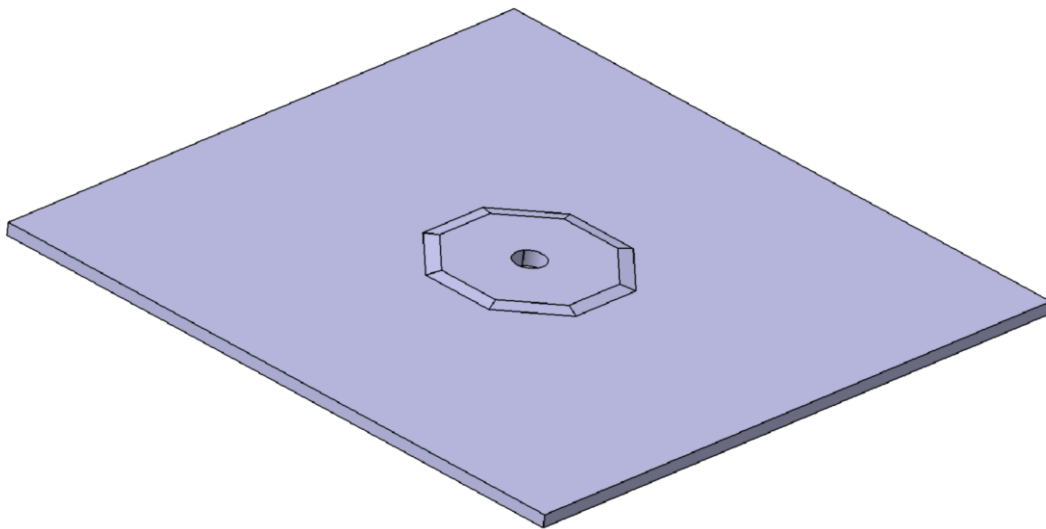


Figure 54: Hole in panel - modified to suit AFP process

Whilst the AFP produced laminate can be manufactured at a higher speed, with greater accuracy and a higher degree of repeatability, the AFP pad-up weighs 496g, compared to the hand-laminated pad-up which weighs only 287g, which is a 42% difference.

5.7 Design step for short fibres (second example)

In the design step for short fibres, relating to the 14th step in the overall design process, the panel of expert designers carrying out the FMEA identified a design risk that is notorious amongst AFP experts, but is never referenced in any design guidelines for people designing for AFP. It involves a material characteristic where the internal tension within the composite tape exceeds the adhesion limits attaching that tape to the rest of the laminate. The result is the tape springs off the contoured surface and stops further material being deposited.

The likelihood of material springing off the surface of a laminate is dependent on the specific material selected, but typically occurs when a tape is terminated too close to a geometrical feature that introduces tension in the tape, such as wrapping a tape around a small radius 90° corner. This is illustrated in Figure 55, note that the operator has stopped the automated process and used tape to secure the first few tapes to prevent further lifting.

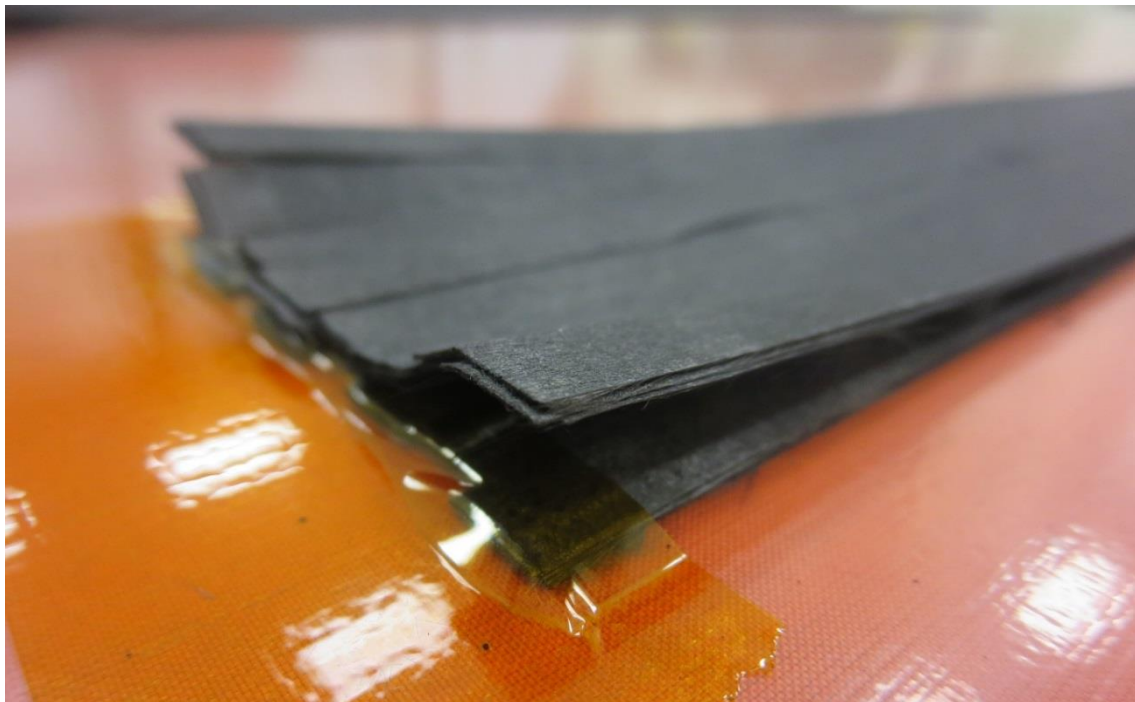


Figure 55: Material tension causing the tapes to lift

5.7.1 Short fibre design objective

The main design objective is to ensure that the tape extensions are added to the detailed design model, particularly if they are inside the trim allowance.

Using an 'L' section component with a variable thickness as an example, the tapes that are too short occur on the diagonal 45 degree and 135 degree plies. This is illustrated in Figure 56. In the design, no allowance is made for these tapes on the edge of the component or where the local thickness is increased. During the manufacturing adaptation of the design, the tapes will be extended at the edge of the component as these extensions are trimmed off at a later productions stage, however the area with local thickness increase inside the part remains unaltered.

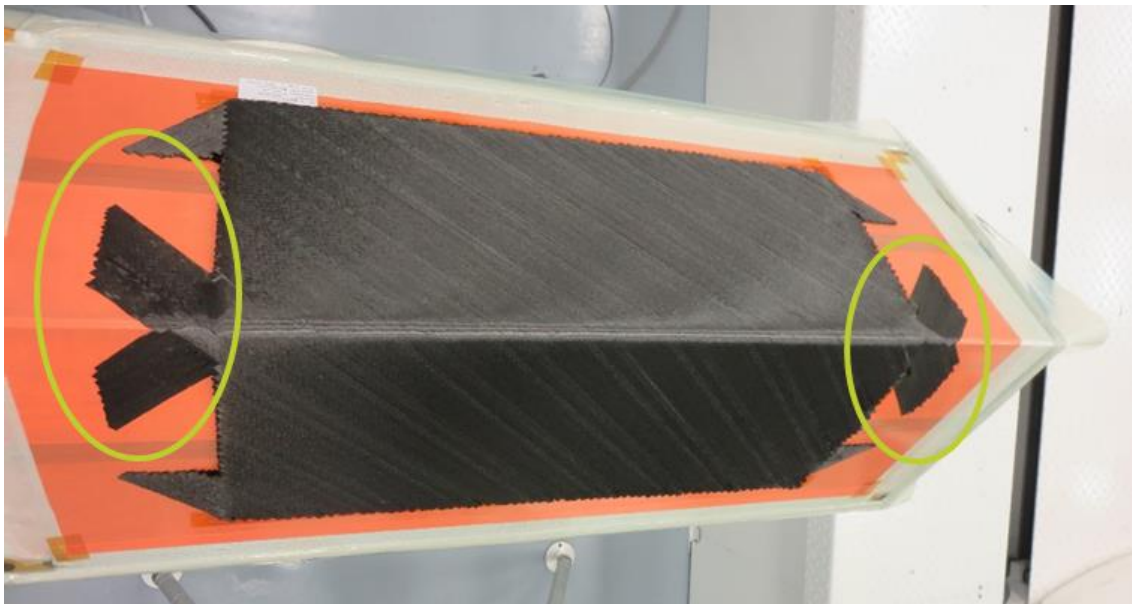


Figure 56: Tape extensions around small radius to prevent tape from lifting

5.7.2 Short fibres manufacturing objective

Short tapes over radii may spring off the laminate and need to be extended, sometimes this is not inside the trim allowance. If the radius is too small, the areas inside the laminate where the thickness is locally increased either need to be extended, or the resulting defects accepted as a concession. A material dependant rule can be established to aid the designer in selecting when to change the boundary shape to account for an extension, and when to leave the

boundary unchanged. This rule is dependent on the radius size for a given material.

5.7.3 Short fibre analysis

Failure Mode: Short fibres not added in areas where tapes are in tension and radius is too small. Results in tapes lifting and causing defects in laminate.

Effect(s) of Failure: Fibres lift off laminate after deposition, tapes laid over the top of these unsecured laminates trap them in sub-optimal orientations causing overlaps and gaps in the laminate.

Root Cause: The material's natural spring overcomes the adhesion over a short length. Extending the length increases adhesion, or increasing the radius can reduce the effect of tension in the material.

Design Severity: Low – Tight radii are less desirable in composite structures than in metallic structures, reducing the occurrence. Increasing the radius is often simpler than accounting for extended tapes at an internal ply boundary.

Manufacturing Severity: Medium – Not extending the tapes at the ply boundary for a tight radius is likely to result in a defect in the laminate. Defects can be reduced by manual intervention, such as stopping the automated deposition and manually using a heat-source to repair any displaced tapes.

Corrective Action: Liaise with design - it may not be practical to add extensions without changing internal surface definitions and interfaces, or there may be a preference to increase the radius or alter the geometry to reduce the tape tension.

5.8 Design step for high consolidation mitigation (third example)

Pre-impregnated composite material and thermoplastic composite material already contain the fibre and matrix. These materials need to be consolidated to remove trapped air and cured. Dry fibre material only contains a small percentage of required matrix, and the missing matrix is infused or injected after the laminate has been deposited. AFP dry fibre laminates must be laminated with minimal

trapped air so that the geometry does not significantly change when they are consolidated, but must also not be over-consolidated since this alters the permeability of the laminate and prevents the infusion of a resin.

During the AFP deposition process, the AFP roller can reduce contact area with the laminate due to the geometry of the laminate, momentarily increasing the effective consolidation force. Features such as ramps and corners cause local areas to become over-consolidated, making them difficult to infuse or inject with resin. Figure 57 shows a corner preform that was created by hand using uni-directional dry fibre. The corner is not over-consolidated and can be infused as a baseline in 50 minutes. Figure 58 shows an equivalent preform to Figure 57, with the same material and lay-up, however it has been manufactured using AFP and therefore features an over consolidated corner section where the roller contact area with the laminate has reduced but the compaction force has been constant. The same infusion strategy was used, with the same resin, however this component took 1 hour 40 minutes to infuse.

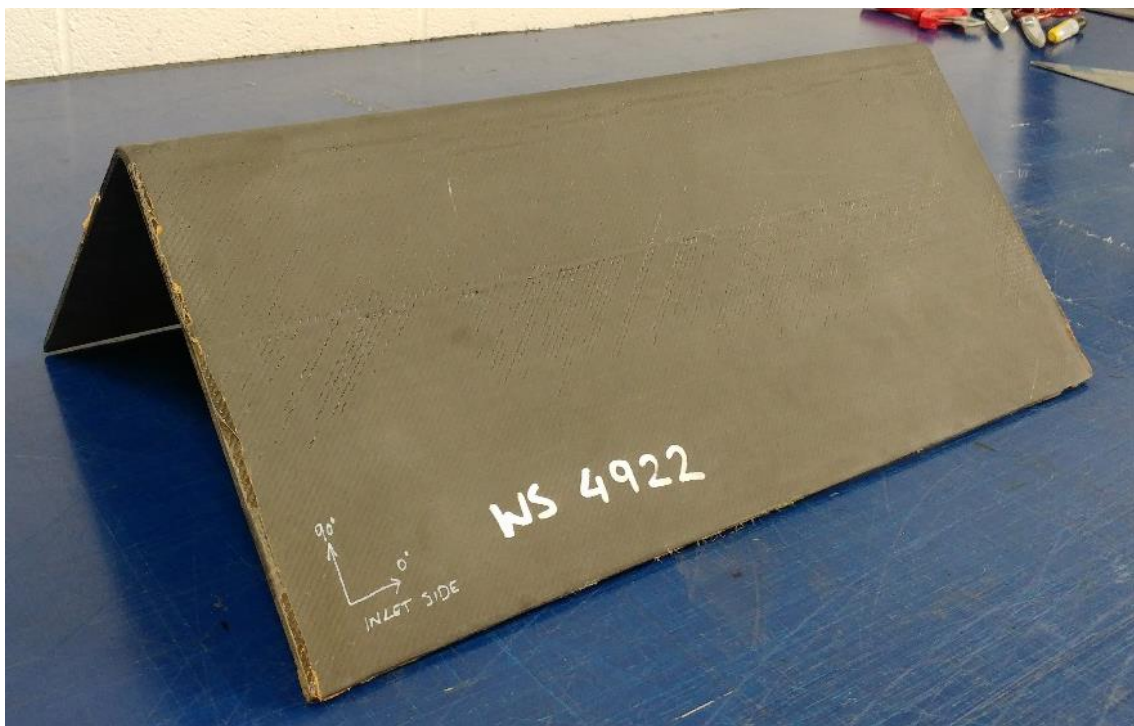


Figure 57: Hand laminated dry-fibre preform, infused in 50 minutes

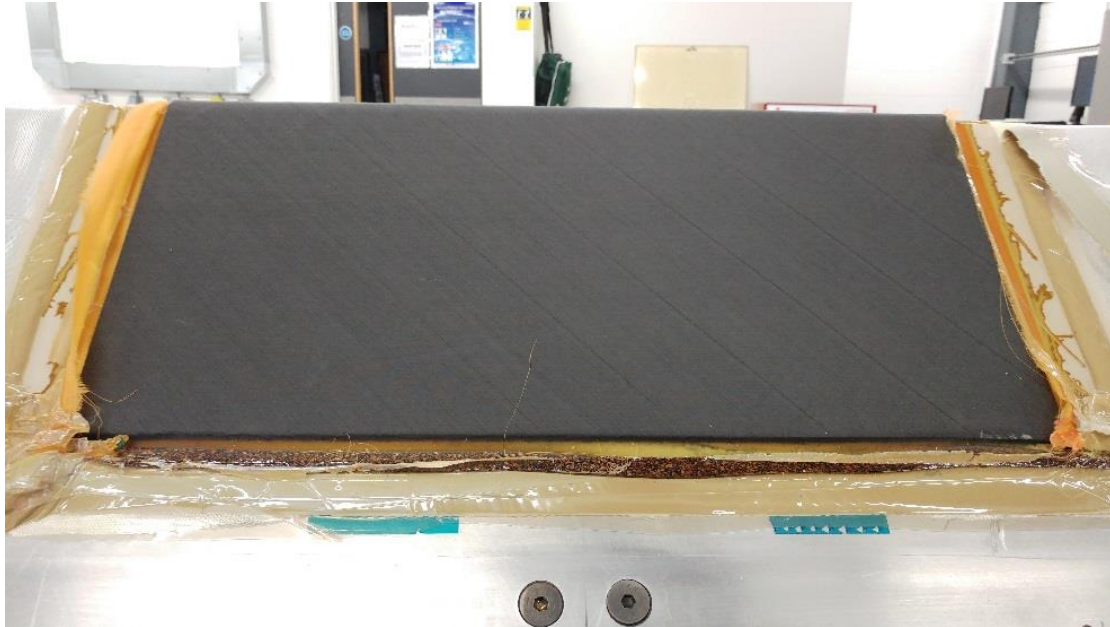


Figure 58: AFP deposited dry fibre preform, no gaps between courses/tows, infused in 1 hour 40 minutes

The AFP deposition strategy can be adapted to create resin flow channels so that poor permeability can be mitigated in areas of over-consolidation. By introducing deliberate gaps between the tows, resin channels can be used to increase the resin flow to areas of poor permeability.

5.8.1 High consolidation design & manufacturing objectives

Highlight the areas in a structure where poor permeability is likely to occur, and evaluate the feasibility of steering fibres locally to introduce gaps between courses that will act as resin flow channels. Steer fibres in converging or diverging paths to enable resin flow channels to be aligned through the laminate around the target areas. Where possible, the designer should attempt to maintain target fibre angles and a fibre volume fraction within design limits for the component.

5.8.2 High consolidation analysis

Failure Mode: Geometrical features that become over-consolidated during automated deposition. If resin cannot flow to and then through these areas, the laminate cannot be fully infused and areas of dry fibre are left.

Effect(s) of Failure: When resin cannot flow through an area of the laminate, it flows around the area causing a dry patch. Once resin has flowed from the laminate inlet, to the laminate outlet, there is no way to force resin to impregnate the dry patch and the infusion of the laminate fails.

Root Cause: The fibres are over-compacted leaving insufficient air content, or permeability for the resin to flow through the full preform.

Design Severity: Low – Any component with complex geometrical features will require a degree of fibre steering when generating ply coverage. Exploiting the steering opportunities to also improve resin flow is unlikely to negatively affect the design performance.

Manufacturing Severity: High – Failure to fully infuse a dry fibre laminate results in the entire laminate being scrapped.

Corrective Action: If the maximum quantity of gaps has been achieved and there are still insufficient resin flow channels for a feature, then the designer must change the geometry to reduce the effects of consolidation.

5.9 Concluding remarks

This chapter presents the design process for systematically identifying and then implementing design for manufacturing principles for a composite component design. In order to demonstrate this, the design process is described and then the resulting process flow and process FMEA steps that have been generated using the process are listed in the appendices. Three industrially relevant examples have been used to demonstrate the process steps and resulting corrective design actions which can be addressed in the earlier stages of the design lifecycle.

A potential limitation associated with using an FMEA approach is that the analysis and suggested corrective actions of each potential failure mode are limited by the experience of the team carrying out the FMEA. In this work, the laminate chosen to test the process closely resembles the structure of a section of aircraft wing, with strong similarities to aircraft fuselages too. The team involved in the FMEA

all have at least 10 years of individual experience designing and manufacturing aircraft wings, which helps to reduce the likelihood of not being able to identify all the potential failure modes. No alternative to aerospace components have been considered in this work, limiting it to typical grid-based aerospace structural designs.

The FMEA process has delivered a systematic approach to valuating design steps and the corrective actions enable this design process to be used as a strategy to help designers take into account the design for manufacturing considerations required for automated manufacturing processes. The use cases described in this chapter do not necessarily transcend multiple industrial sectors, and have a focus towards aerospace components and the automated fibre placement manufacturing process.

The new and novel lessons learnt show that the use of FMEA under the context of a 'failure being an event that is not positive for the optimum manufacturing process' is a new approach to developing a generic design process. The approach could be adapted to suit other manufacturing processes, or design process flows where adequate design and manufacturing expertise is available. This chapter demonstrates that a generic process can be developed for DFM of composite components.

6 VALIDATION OF PROPOSED DFM PROCESSES AND TOOLS

The purpose of this chapter is to demonstrate and validate the design process described in chapter 5 using an industrially relevant demonstration as a use case. The component selected is a composite laminate that incorporates multiple complex features that are known to cause difficulties when manufactured using automated deposition technologies. The component was created to address the requirements of the following NCC customers, Airbus UK, Rolls Royce, Leonardo Helicopters, BAE Systems, GKN Aerospace, QinteiQ and GE Aviation.

The design process described in Appendix A contains 28 steps. Whilst each of these steps is required to progress the design from concept to a physical part, not all of the steps contain manufacturing considerations which significantly alter the design. This chapter highlights the design process steps where a manufacturing decision causes a significant impact on the component design, and describes the rationale and magnitude of the resulting change in the design.

6.1 Introduction

The use case described in this chapter has been specifically designed to provide challenging geometrical features when the component is manufactured using an AFP manufacturing system. The chosen system uses 6.35mm wide dry fibre tapes and the NCC's Coriolis AFP system is capable of laying a range from single tapes to a maximum of 8 at a time. The heating system for depositing the tapes uses a class 1 laser, and therefore no operators are allowed in the same room as the AFP machine while it is depositing material. Manual interaction with the component during automated deposition is therefore highly undesirable.

The component is illustrated in Figure 59. The corner angle is 90° with an internal radius of R10mm. There is a change in thickness from 30mm to 10mm with a rate of change of 1 in 5 or 11.6° that results in a tapered radius. The increase in thickness is localised to account for a large penetration through one flange. The additional material increases the load transfer around the holes, where the fibres

are non-continuous. The component was designed using the CATIA V5-6R2012 3D CAD software.

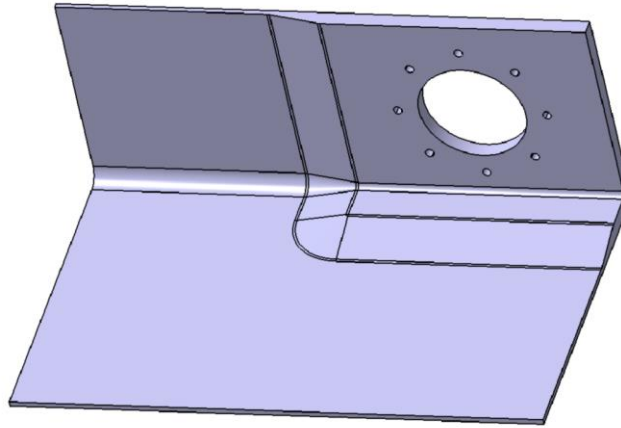


Figure 59: Initial concept showing a 90 degree corner laminate with variable thickness

The concept design and preliminary design information such as material thicknesses and thickness laws are captured in a 2D array using Microsoft Excel, and the DFM tool described in chapter 4 was used to apply design rules to the laminate. The tool is referred to as mPDA, referring to Airbus's manufacturing ply design analysis tool and uses a C++ routine which is run from Excel using the standard 2D arrays for sizing data.

6.2 Selection of the use case

The use case was selected because it offered several key advantages over other suitable industrial components, these advantages are:

- The component is part of the NCC's core research program, so the design features are proposed and agreed with Airbus UK, Rolls Royce, Leonardo Helicopters, BAE Systems, GKN Aerospace, QinteiQ and GE Aviation.
- The author is responsible for leading and delivering the project.
- The component design and development is reviewed in front of the industrial sponsors on a monthly basis.

- The features incorporated into the design are chosen specifically to push the manufacturing process to the limit of what has previously been demonstrated.

Only one use case was selected instead of a multiple use-case validation because of the nature of the NCC core program. This single use case is endorsed by eight aerospace and defence companies, and has been tailored to address their primary development challenges associated with automated deposition of composite materials. The eight companies endorsing the use case manufacture a range of different composite products, such as aircraft wings, gas turbine engines and rotor blades, and some are competitors like GE and Roll Royce, who both manufacture gas turbines with composite intake blades. As a result, the features of the use case must be representative of relevant industrial challenges, but also remain generic enough to not be specific to any particular company product. This means that the use case is both industrially relevant and suitably generic to be used as validation of this research.

6.3 Methods followed in this research

In order to follow all of the process steps identified in the process flow in section 5.4, a table of corrective actions was required. The table is shown in section 5.4.5, and lists the 28 stages required to produce a design that can be manufactured using the AFP manufacturing process. The use case was identified as a concept, and then each of the 28 steps was followed to mature the design to a point where the component was physically manufactured.

The concept was created to deliberately include geometrical features that are challenging to manufacture using the AFP process, and dry fibre material was selected to highlight complexities when the component is infused. The process steps which caused any of the following impacts are described in detail in this chapter:

- Changes in structural performance, such as changing ply sequences
- Changes in component mass, such as increased thickness
- Changes in ply shapes or overall geometry

- Changes in fibre orientation and alignment

Section 6.4 describes the significant process steps in greater detail, using the use case as an example. The concluding remarks compare the original concept design to the final produced design in terms of design intent, ability to manufacture and overall component mass.

The use case concept was created by the author, and the project to create the design according to the design process and to manufacture the physical part was also led by the author. The photographs and metrology data presented in section 6.4 are the work of Laura Veldenz, who as part of her EngD research is evaluating the dry fibre AFP process [100] [101]. Laura's research has played an important part in developing a better understanding of the dry fibre AFP process, without which the manufacture of a physical component of significant complexity would have been extremely challenging.

6.4 Industrial use case

This section describes the design lifecycle and physical manufacture of the final use case component, using the NCC's Coriolis AFP system. The use case is divided into six sub-sections, 6.4.1 to 6.4.7, which group similar design steps together. The groupings are described in Table 21. The method of applying each design step is explained in Table 22.

Table 21: Sub-sections of use case and the steps of the design process they address

Section	Design stage addressed																											
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
6.4.1				X	X	X	X																					
6.4.2								X			X	X	X															
6.4.3														X													X	X
6.4.4															X	X	X	X	X	X	X	X	X					
6.4.5															X	X	X	X	X	X	X	X	X					
6.4.6																								X	X	X		
6.4.7				X	X	X	X	X			X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

Table 22: Descriptions of how each research step was applied

Section	Description	How was the design step applied?
6.4.1	Material thickness and thickness laws	In the use case these manufacturing constraints were automatically applied using a digital toolset which uses the ply continuity methodology developed in section 4.
6.4.2	Minimum cut lengths	The generation of minimum cut length options is automatically embedded in the CATIA design tool, but the option selection is manual.
6.4.3	Tooling design	The tool design process step is entirely manual and carried out by the designer.
6.4.4	Axis system and fibre angles	Basic fibre geometry (straight trajectories) can be automated, however the custom guide curves described in this research are created manually by the designer.
6.4.5	Steering of fibres	The generation of steered fibres can be automated using a macro function in the CATIA design tool, but was carried out manually in this research.
6.4.6	Consolidation and gaps	The areas of high consolidation were identified manually and the gaps were introduced manually by the designer.

The initial process steps 1 to 3 are not part of the descriptions used in the subsections of the use case. These process steps check the quality of the initial CAD data which results in a pass or fail decision. The use case passed all of these checks.

Process steps 9 and 10 are also omitted from the descriptions used in the sub-sections of the use case. These steps add the composite material properties to the design, and create a visualisation of the laminate. The material for the use case was identified at the start of the project, so these two process steps were not required.

6.4.1 Material thickness and thickness laws

This section refers to the design process steps 4, 5, 6 & 7 listed in Appendix A. The manufacturing considerations are to:

- 1) Generate a grid system for mapping data from 2D to 3D
- 2) Add material to original sizing concept in order to achieve feasibility
- 3) Re-sequence plies to improve ply continuity by up to 10%
- 4) Improve manufacturing evaluation scores where possible

The design process steps 4 to 7 relate to the process of generating the sizing data and ensuring that the sized structure can be manufactured.

The material thickness requirements are basic for this concept compared to a typical aircraft structure, with the standard component required to be at least 10mm thick and consisting of a 20/70/10 layup (20% fibres along the axis of the bend, 70% of the fibres diagonal, and 10% across the radius). The increased thickness pad-up must be 30mm thick, but with a more uniform quasi-isotropic layup of 25/55/20 to help divert load around the broken fibres, but still retaining a small bias towards diagonal and 0 Degree plies. The material chosen has a cured-ply thickness of 0.254mm.

6.4.1.1 Generate a grid system for mapping data from 2D to 3D

By using the mPDA tool to automatically apply the design rules listed in section 3.3.2, the thicknesses and thickness laws can be converted into manufacturing optimised stacking sequences. The 3D shape has to be translated into a 2D array in order for mPDA to be run, and the schematic of how this shape is converted into a 3 by 4 array is illustrated in Figure 60.

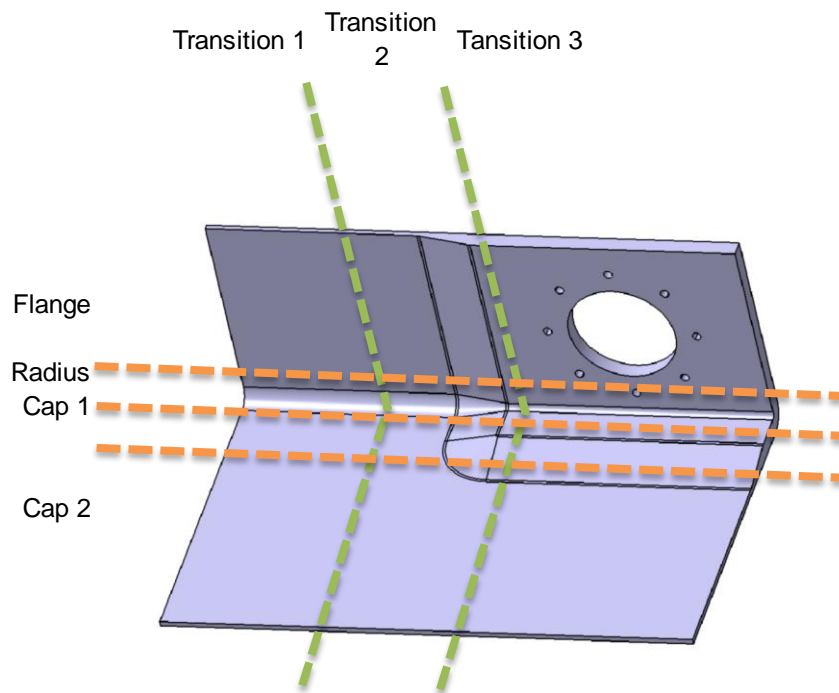


Figure 60: Schematic showing how the demonstrator can be translated into a 2D array

The 2D array shows that there are only 2 different laminate properties across the 12 cells. However the way that each requirement is processed is different. In this design, first the thickness law is selected based on the loads that the structure will have to resist. In the case of the 10mm thick area, a biased laminate for diagonal plies shows that the structure is expected to resist torsion rather than buckling loads. Once the thickness law is selected, a stress analysis tool selects an appropriate thickness of material to satisfy the load requirements.

6.4.1.2 Add material to original sizing concept in order to achieve feasibility

From a manufacturing perspective, selecting the thickness law and thickness without considering manufacturing constraints does not always generate the correct design concept. The material thicknesses requested are not divisible by the ply thickness, and when the thickness laws are applied, essential conditions such as having a balanced and symmetrical laminate are not satisfied. These

original requirements are shown in Table 23 for thickness and in Table 24 for thickness law.

Table 23: 2D array showing the target material thicknesses for the concept

	Transition 1	Transition 2	Transition 3
Flange	10mm	10mm	30mm
Radius	10mm	10mm	30mm
Cap 1	10mm	10mm	30mm
Cap 2	10mm	10mm	10mm

Table 24: 2D array showing the target thickness laws for the concept

	Transition 1	Transition 2	Transition 3
Flange	20/70/10	20/70/10	25/55/20
Radius	20/70/10	20/70/10	25/55/20
Cap 1	20/70/10	20/70/10	25/55/20
Cap 2	20/70/10	20/70/10	20/70/10

6.4.1.3 Re-sequence plies to improve ply continuity by up to 10%

The mPDA tool was developed to automate the application of manufacturing constraints to the initial design requirements, and when run on this use case demonstrator, the resulting thicknesses and thickness laws are different to the original design intent. The mPDA results are shown in Table 25 for revised thicknesses, and Table 26 for revised thickness laws.

Table 25: 2D array of new material thicknesses, modified at preliminary design stage

	Transition 1	Transition 2	Transition 3
Flange	10.668mm	10.668mm	30.734mm
Radius	10.668mm	10.668mm	30.734mm
Cap 1	10.668mm	10.668mm	30.734mm
Cap 2	10.668mm	10.668mm	10.668mm

Table 26: 2D array of new thickness laws, modified at preliminary design stage

	Transition 1	Transition 2	Transition 3
Flange	24/57/19	24/57/19	24/56/20
Radius	24/57/19	24/57/19	24/56/20
Cap 1	24/57/19	24/57/19	24/56/20
Cap 2	24/57/19	24/57/19	24/57/19

6.4.1.4 Improve manufacturing evaluation scores where possible

The effects of applying laminate manufacturing constraints can be seen in both zones as a slight increase in thickness, and a slight deviation in the thickness law percentages.

The thickness laws are converted into explicit stacking sequences:

10mm [20/70/10] = 10.668mm

[-45/45/0/0/0/-45/45/90/-45/45/0/-45/45/90/-45/45/90/-45/45/90/0//Mirrored]

30mm [25/55/20] = 30.734mm

[-45/45/0/0/0/-45/45/90/-45/45/0/0/0/-45/45/90/-45/45/0/0/0/-45/45/90/-
45/45/0/0/0/-45/45/90/-45/45/0/0/0/-45/45/90/-45/45/90/-45/45/90/-45/45/90/-
45/45/90/-45/45/90/-45/45/90/-45/45/90/0//Pivoted around last 0]

The effect of these changes on component mass is an increase of 4%, with the component gaining 1.065kg. This mass gain is unavoidable as it is a result of applying manufacturing constraints to a design, however the practice of identifying the mass gain at the earliest possible stage in the design lifecycle is beneficial. This example validates the research by identifying the additional mass at the conceptual design stage before a CAD model had been created.

6.4.2 Minimum cut lengths

This section refers to the design process steps 8, 11, 12 & 13 in Appendix A, with the following manufacturing constraints requiring consideration:

- 1) Adjust positions of ply boundaries and ramp rates to suit manufacturing constraints
- 2) Add supporting geometry to the CAD model to provide multiple options for generating ramps
- 3) Add minimum cut lengths into CAD model for all plies affected

The design process steps 8, 11, 12 and 13 relate to the process of designing the ply boundaries and associated ramp rates while considering the process specific manufacturing constraints. In this use case, the main constraint that was not accounted for in the conceptual design was the minimum cut length associated with the AFP manufacturing process.

6.4.2.1 Adjust positions of ply boundaries and ramp rates to suit manufacturing constraints

The original use case design, once adjusted for ply thickness and manufacturing rules can be manufactured by hand without any geometrical modification. In order

to use an automated deposition system such as AFP, the design must be adapted to account for the machine constraints.

6.4.2.2 Add supporting geometry to the CAD model to provide multiple options for generating ramps

The minimum cut length for the NCC's Coriolis AFP machine is 100mm. In order to account for this, the area identified as Cap1/Transition 3 must be increased to at least 100mm. If this is not implemented, then the short fibres cannot be deposited in the corner of the pad-up. Figure 61 shows the original design with the penetrations removed.

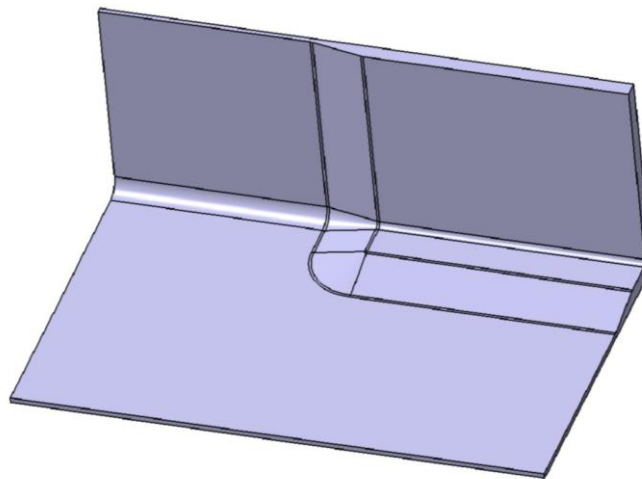


Figure 61: Original use case concept, with hole feature removed

6.4.2.3 Add minimum cut lengths into CAD model for all plies affected

Figure 62 illustrates the changes required to account for minimum cut length, with penetrations removed from the model.

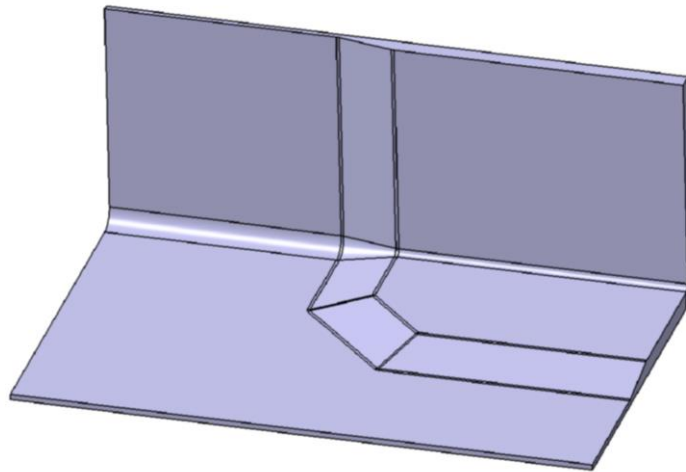


Figure 62: Revised concept adjusted for minimum cut length considerations

The changes cause the design to further increase in mass by 10% adding an additional 2.591kg of material to the design. It is important to note that this additional material increases the stiffness and strength of the component, so it should be identified prior to completing the stress analysis stage of the design lifecycle if the structural benefits are to be taken into consideration.

This section of the use case validates the research by physically altering the geometry of the component to enable it to be manufactured using an automated deposition system.

6.4.3 Tooling design

This section refers to the design process steps 14, 27 & 28 in Appendix A. The following manufacturing considerations must be accounted for in the tool design:

- 1) Add material extensions in areas where tight radii are close to ply boundaries
- 2) Check position of tool in AFP cell for machine access
- 3) Investigate machine parameters for access to the tool

The design process steps 14, 27 and 28 relate to the tooling design with process step 14 focusing on the early lifecycle opportunities to improve the tooling design,

and steps 27 and 28 focusing on the validation of the tooling design prior to manufacture.

6.4.3.1 Add material extensions in areas where tight radii are close to ply boundaries

The AFP tool needs to be larger than the component to allow the AFP machine head to make contact, and pre-load the head before material is fed onto the tool surface. The tooling is designed to be mounted on a table, so that the 150N of force applied by the AFP machine is transferred to the ground. The initial tooling concept is shown in Figure 63.

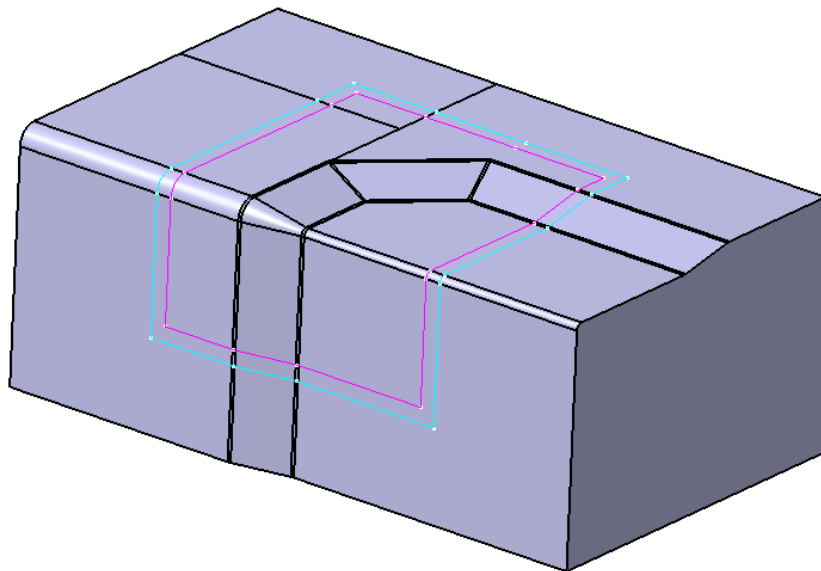


Figure 63: Initial tool design

6.4.3.2 Check position of tool in AFP cell for machine access

It is really important that the tool is checked using a simulation of the AFP process to ensure that the component surface can be reached by the AFP machine. If the AFP machine cannot access the tool surface because of the risk of collisions, then the tool cannot be used. Because the tool was being installed on a pre-existing table in the AFP cell, the initial concept tool was positioned too high

relative to the robotic AFP machine, and the component surface needed to be rotated 20° backward to enable the AFP head to access the front face of the tool without causing the laser fibre optic cable to collide with the table. By performing this simulation as soon as the component preliminary design had finished, before any ply data had been created, the tool design could be changed before the tool needed to be manufactured. The location of the revised tool in the AFP cell is shown in Figure 64.



Figure 64: Illustration of tool checks in AFP programming environment

6.4.3.3 Investigate machine parameters for access to the tool

The final tool design is shown in Figure 65. The tooling material is carbon fibre, allowing the component to be laid directly onto the tool during the AFP process, and staying on the tool for the higher temperature infusion process that requires a 180°C environment.

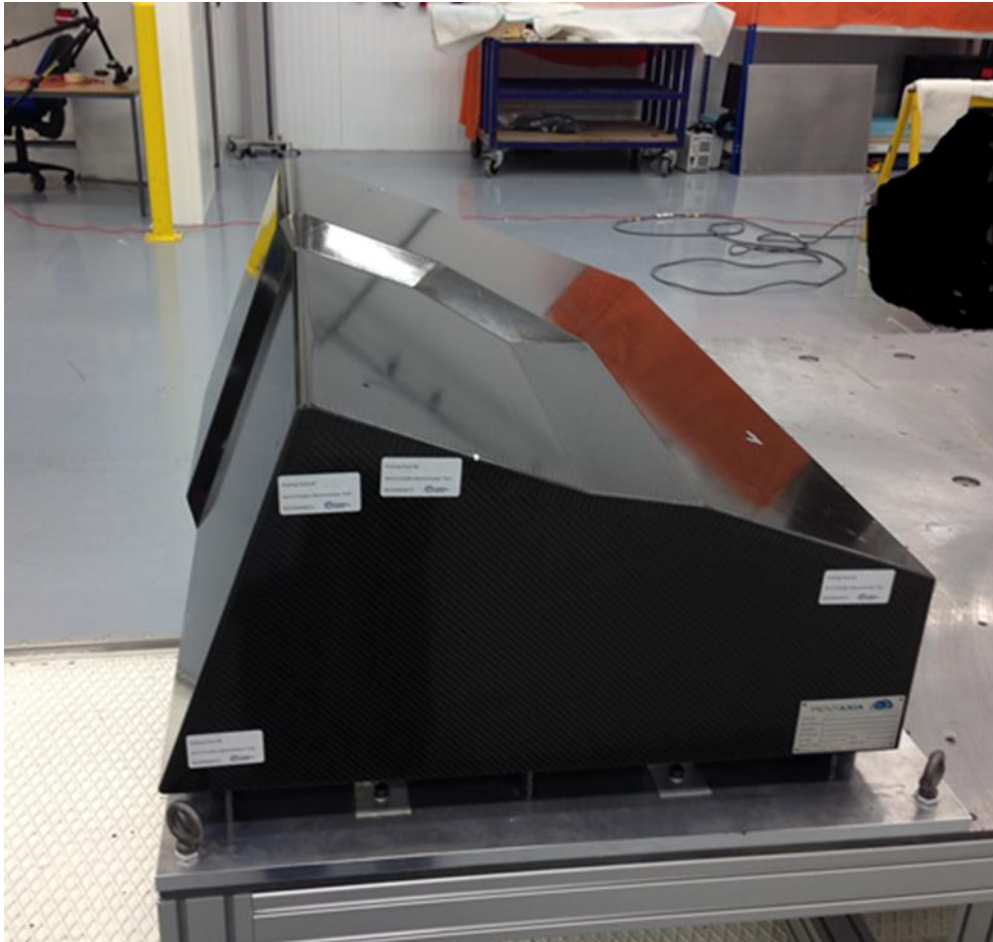


Figure 65: Photograph of final layup and cure tool

The tooling design was improved during the initial investigations into its compatibility with the AFP cell. This enabled the tool to be used successfully in the AFP cell without the need for modification, and validates the benefits of performing tooling checks at the earliest point in the design lifecycle.

6.4.4 Axis system and fibre angles

This section refers to the design process steps 15 to 23 in Appendix A. The following manufacturing considerations must be accounted for in the detailed design:

- 1) Feedback AFP simulated fibre angles to stress for validation
- 2) Add convergence zones or change geometrical surface to cope with geodesic fibre paths that are too extreme

The design process steps 15 to 23 relate to the axis system and fibre angles. The same steps also relate to the fibre steering, but steering is describes in section 6.4.5.

The design features an axis system on one face which is used to define the orientation of the individual plies. The axis system needs to be transposed from the initial face to the second face in order to establish the ideal direction of the fibres. The transposed axis system does not account for the tapered radius and the effect this has on diverging and converging fibre angles.

6.4.4.1 Feedback AFP simulated fibre angles to stress for validation

The effects of transposing the axis system can be seen clearly if the component is simplified to focus only on the effects of the tapered radii. Transposing the desired fibre angles onto the two faces of the component, but ignoring the radii produces the correct fibre orientations in the flat flange and cap areas of the component. This is illustrated in Figure 66.

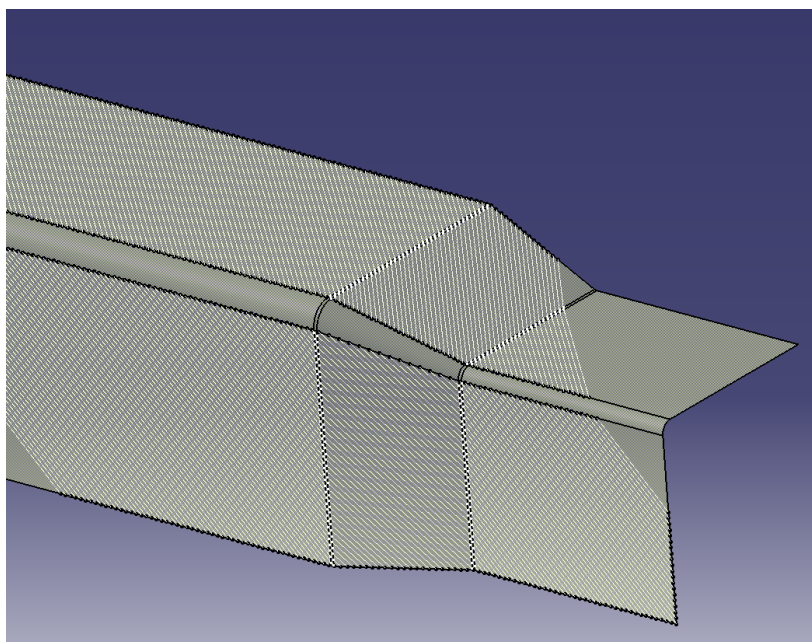


Figure 66: Fibre angles transposed onto the cap and flange faces as the designer intended (No coverage for radii)

If the radii is taken into consideration, then the geodesic path of the fibre is disrupted by the tapered geometry, and the fibre angles diverge and converge on

the cap and flange areas of the component, as illustrated in Figure 67. The final fibre paths are fed back into the stress analysis of the part to ensure that the programmed fibre trajectories meet the original design intent.

The geodesic fibre path represents the path which is least likely to buckle, lift or twist when deposited, so a compromise between the fibre angle requested in the original design, and the fibre angle which creates the least defects is required. Steering the fibre angle around a radius that is large enough to avoid generating its own defects is used to create a compromised fibre trajectory, resulting in reduced manufacturing defects, but areas of the component which deviate from the designed fibre angle.

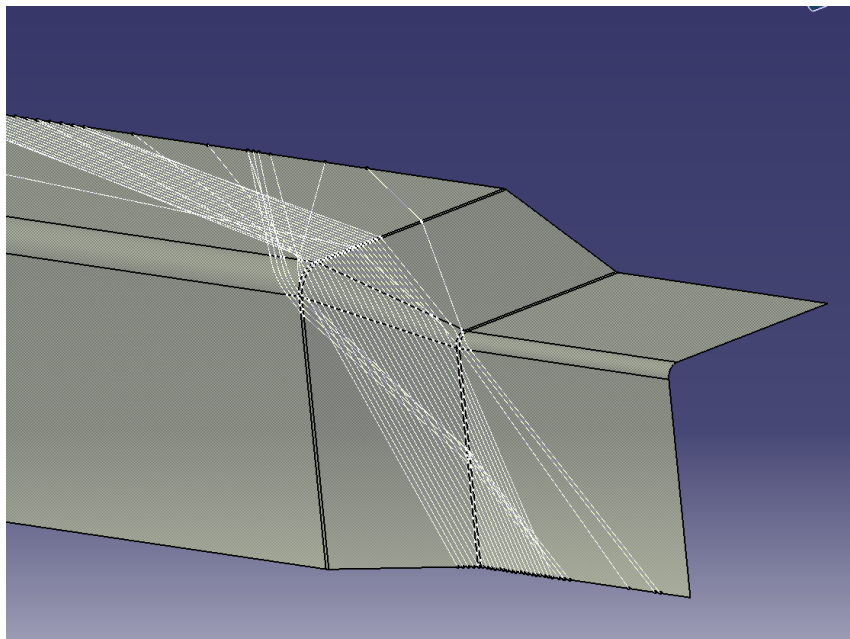


Figure 67: Divergence and convergence of fibres when the effects of the tapered radii are included

6.4.4.2 Add convergence zones or change geometrical surface to cope with geodesic fibre paths that are too extreme

The fibre trajectories created by steering to recover fibre angles introduces gap and in some instances overlaps, although overlaps are typically avoided if possible due to the propagation of surface defects. The gaps and overlaps in each ply are considered a type of allowable defect, however these allowable defects are not allowed to line up through the thickness of the laminate. The

technique for preventing alignment of allowable defects is staggering the trajectories. In the use case, the majority of the gaps occur around the tapered radius, so each ply layer is staggered by offsetting the trajectory guide curve.

The introduction of gaps between carbon fibre tapes can be used to improve the permeability of the highly consolidated radius area and also progressively reduce the effects of steering across the component. For the 0 Degree plies, which follow the radius, a convergence zone is required to accommodate the need to join the cap and flange areas together. This is done by laying single tows along the length of the radii and dropping the tows at the tapered radius. This is illustrated in Figure 68. The gaps created in this ply coverage create uniform voids inside the laminate that can be used to help flow resin to the radius, where poor permeability is predicted.

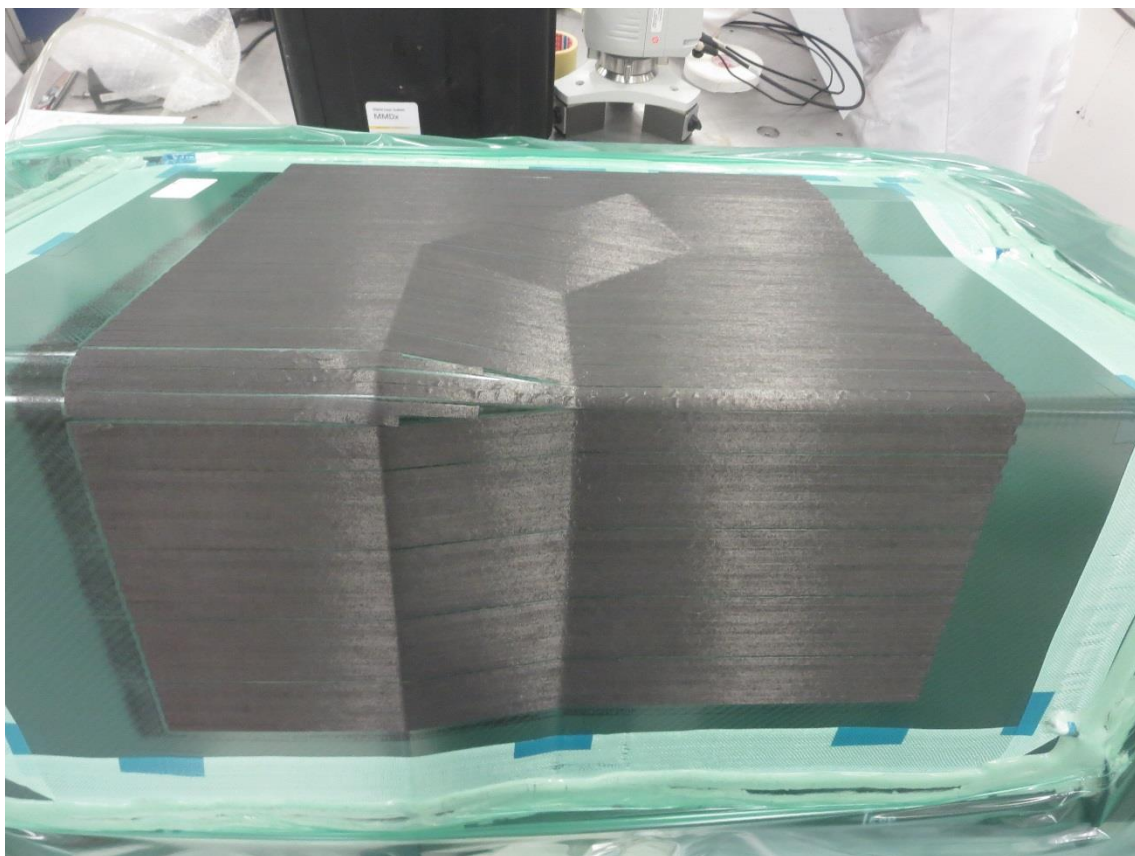


Figure 68: 0 Degree ply coverage showing tow dropping and convergence zone

This section of the design of the use case highlights the amount of manual tailoring of the fibre paths that a designer must carry out. The generic design

process describes the manufacturing corrective actions required, but the digital tools used are not fully automated and success is dependent on ability of the designer to create customised fibre guide curves. The example validates the design process by generating a ply coverage that utilises fibre trajectories that are within allowable limits for gaps, overlaps and angular deviation.

6.4.5 Steering of fibres

This section refers to the design process steps 15 to 23 in Appendix A. The following manufacturing considerations must be accounted for in the detailed design:

- 1) Steering radius and fibre angle deviation should be changed together to mitigate extreme geometry
- 2) Set course gaps, overlaps, stagger and tow drops to suit manufacturing and design constraints

The design process steps 15 to 23 relate to the steering of the fibre paths previously described in section 6.4.4, where the fibre angles and axis system process steps were described.

The geometrical features created by the thicker section of the component, and the radius on the corner of the laminate require the fibres to follow geodesic trajectories to reduce the occurrence of defects. These features are coloured purple and highlighted in Figure 69. The geodesic fibre paths in these areas are less likely to generate manufacturing defects, but also cause the fibres to deviate from the target fibre angles. The deviated fibre paths caused by geodesic regions require steering to reclaim the fibre angles. Steering can be the cause of defects in a laminate, so the proposed corrective action is to steer the fibres before and after the geodesic regions on the flat surfaces to reduce the likelihood of defects.

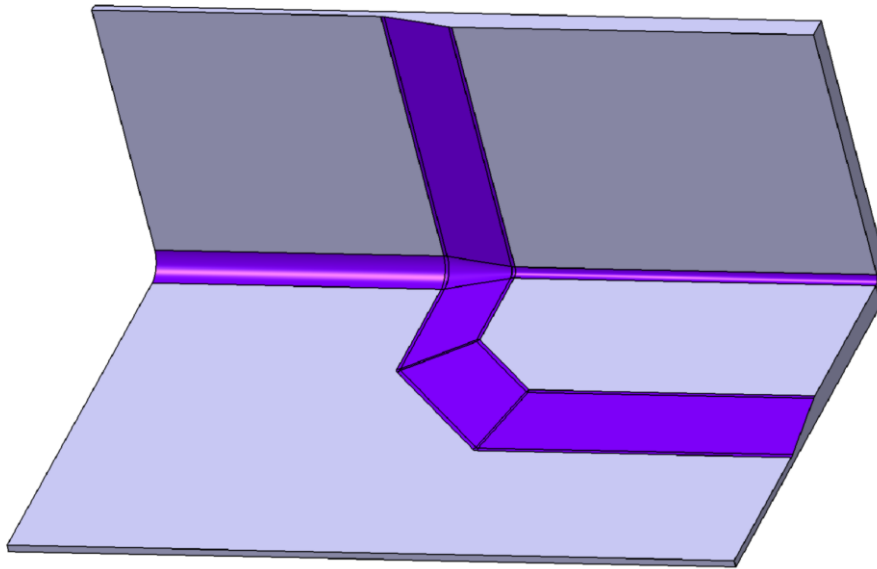


Figure 69: Geometrical features highlighted in purple where geodesic fibre paths are required

6.4.5.1 Steering radius and fibre angle deviation should be changed together to mitigate extreme geometry

The software used to automatically generate the fibre trajectories is Coriolis CADFiber, and the digital tool is capable of creating fibre trajectories using standard fibre strategies. The simulation of the standard fibre trajectories is shown in Figure 70, with a colour map showing the degree of steering in each tape. The standard trajectories are generated by creating a 45 degree fibre path through the most severe feature (the tapered radius), and offsetting that path parallel either side to create the full ply coverage.

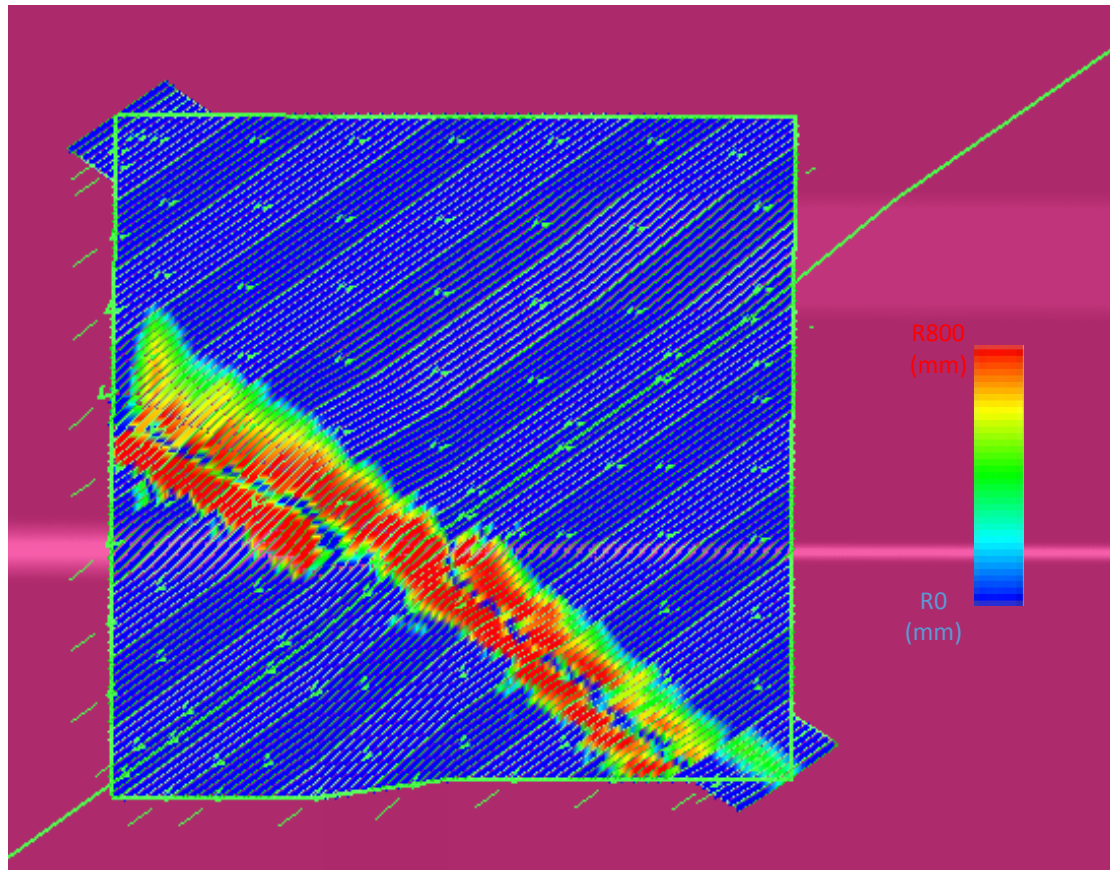


Figure 70: Standard fibre trajectories generated using CADFiber with two sectors

To highlight the problems that this standard strategy creates, the 45 degree ply was programmed and then manufactured. The result is shown in Figure 71 and Figure 72. The tool was covered with a green nylon vacuum bag to make the removal of trial material easier.

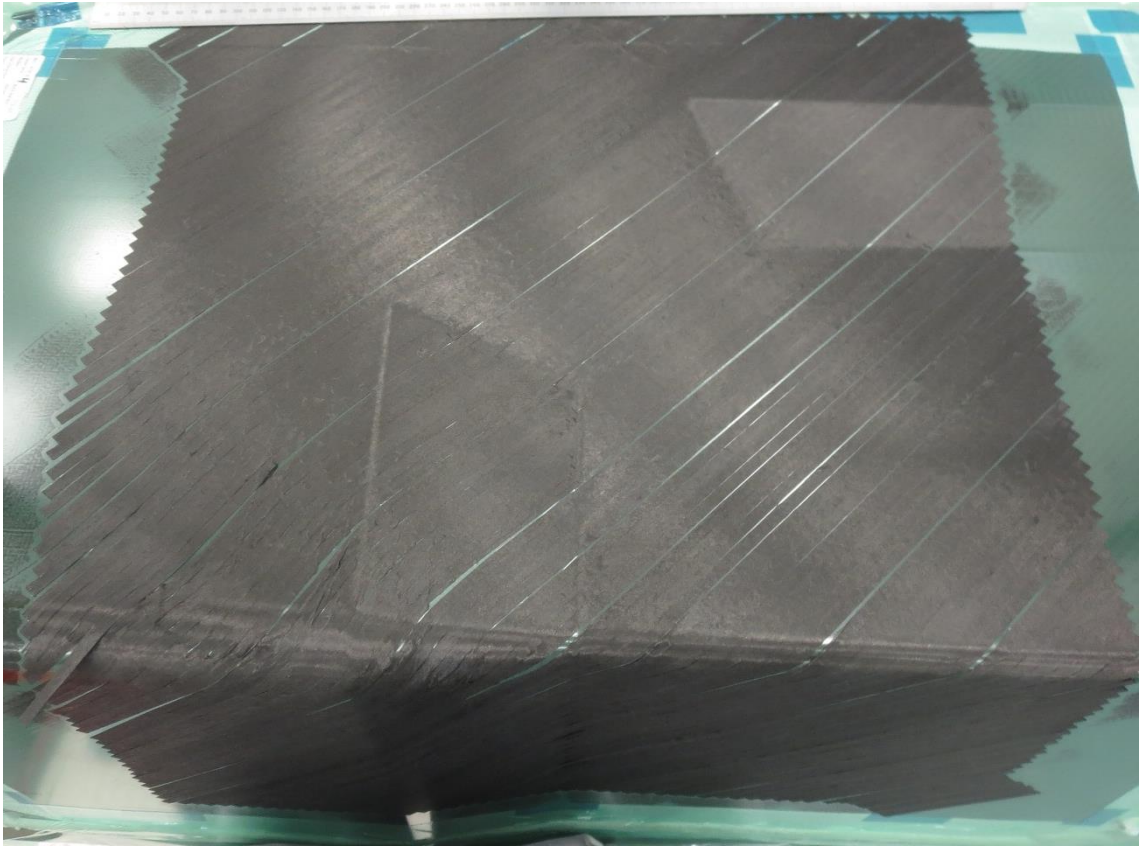


Figure 71: Top view of 45 degree ply using standard fibre trajectories

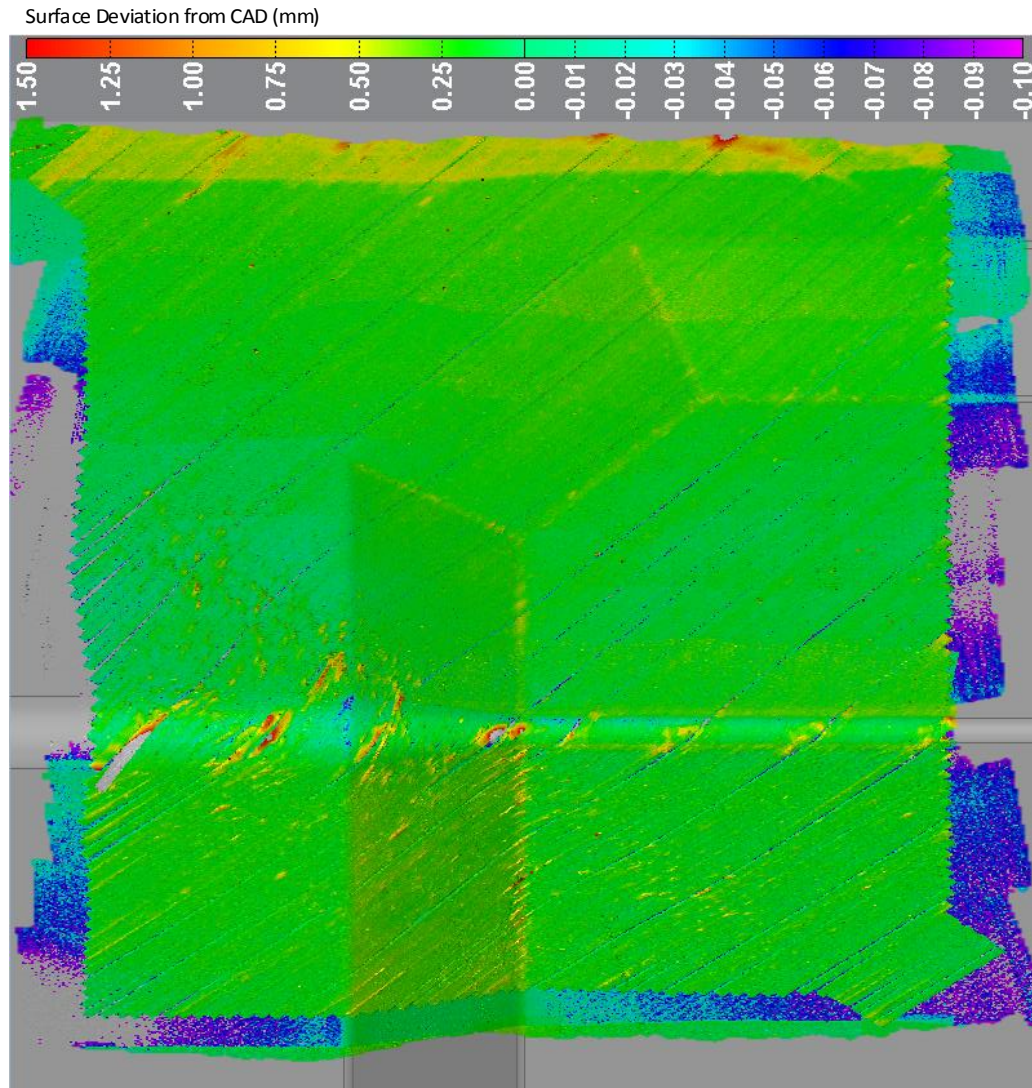


Figure 72: Metrology scan of 45 degree ply using standard fibre trajectories. Areas in red show a defect of 1.5mm thickness, and on the left side of the radius a tape can be seen lifting off the tool surface

The standard fibre coverage was deposited with the machine process parameters that had been optimised using a series of smaller scale trials carried out previously. Unfortunately some severe defects were created along the radius, which can be seen in closer detail in Figure 73. The defects are attributed to a difference in tension between the inner and outer edges of the tapes, typically caused by steering too far from a geodesic fibre path. The metrology scan highlighted that these defects exceeded 1.5mm in thickness which is not acceptable. The metrology scan was performed using a Nikon MCAx portable CMM arm, equipped with a MMD X100 laser scanner. This provided an accuracy

of approximately 100 μ m. The scan results were processed using Polyworks metrology software which computed the image for surface deviation from CAD in Figure 72. The areas shown in grey are areas around the outside of the component which were not scanned.

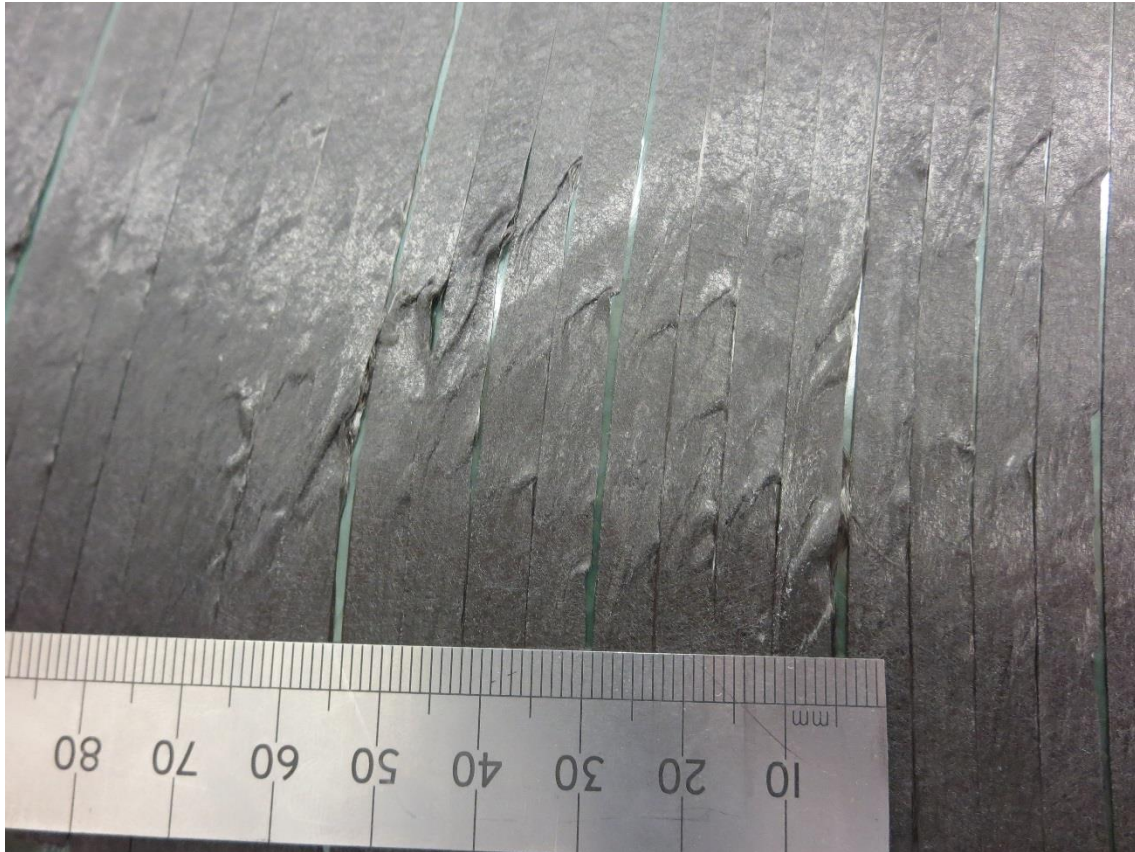


Figure 73: Defects on radius caused by not using a geodesic fibre trajectory

A customised fibre trajectory can be created in CATIA V5 and then be imported into the CADFiber machine programming software. This allows the designer to generate a non-standard fibre trajectory and use fibre steering to distribute the tensions in the tapes that are caused by the geometry over a longer length.

6.4.5.2 Set course gaps, overlaps, stagger and tow drops to suit manufacturing and design constraints

The customised fibre trajectories can be tailored to address two manufacturing corrective actions. Firstly, steering the fibres can be used to reduce the severity of defects in the laminate, and secondly, introducing gaps between the tapes can improve the delivery of resin to highly consolidated areas of the laminate.

The customised fibre trajectories for the 45 degree ply are split into three sectors. The central sector runs through the tapered radius and has the largest amount of steering. The tapes are not laid at a full course width of 8 tows, but in 4 passes of 4 tapes. This enables a variable gap to be introduced between each course of 4 tows, which allows each course to be steered on a different trajectory without risking overlapping with a neighbouring course, and for the gap to aid with resin delivery. Figure 74 shows the central custom trajectory fibres with a colour coded indicator of the amount of steering over the tapered radius.

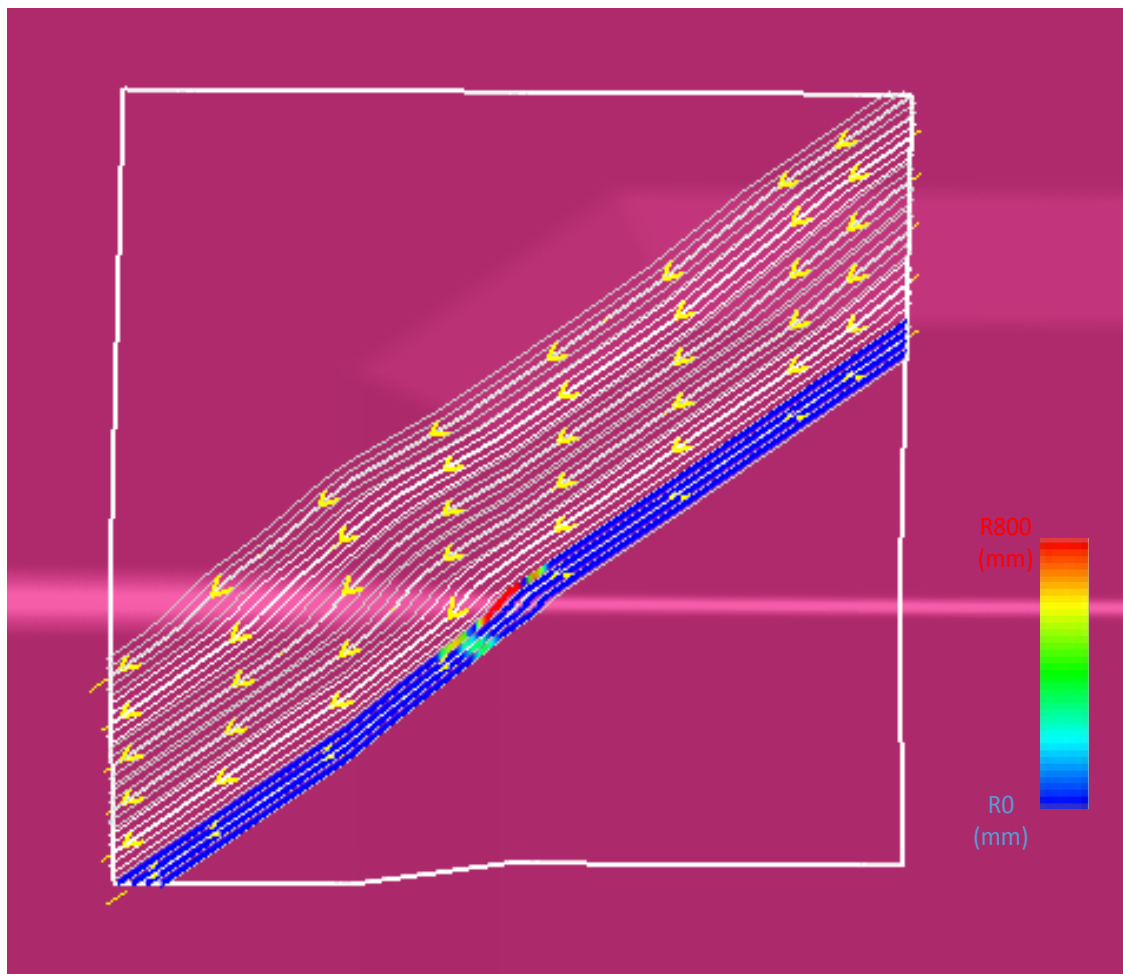


Figure 74: Custom trajectories steered either side of most complex geodesic feature

The upper sector is generated using an offset from the central sector. If further complex features were placed in the upper sector, then it could be broken into

smaller customised sectors with steering. The upper sector is illustrated in Figure 75.

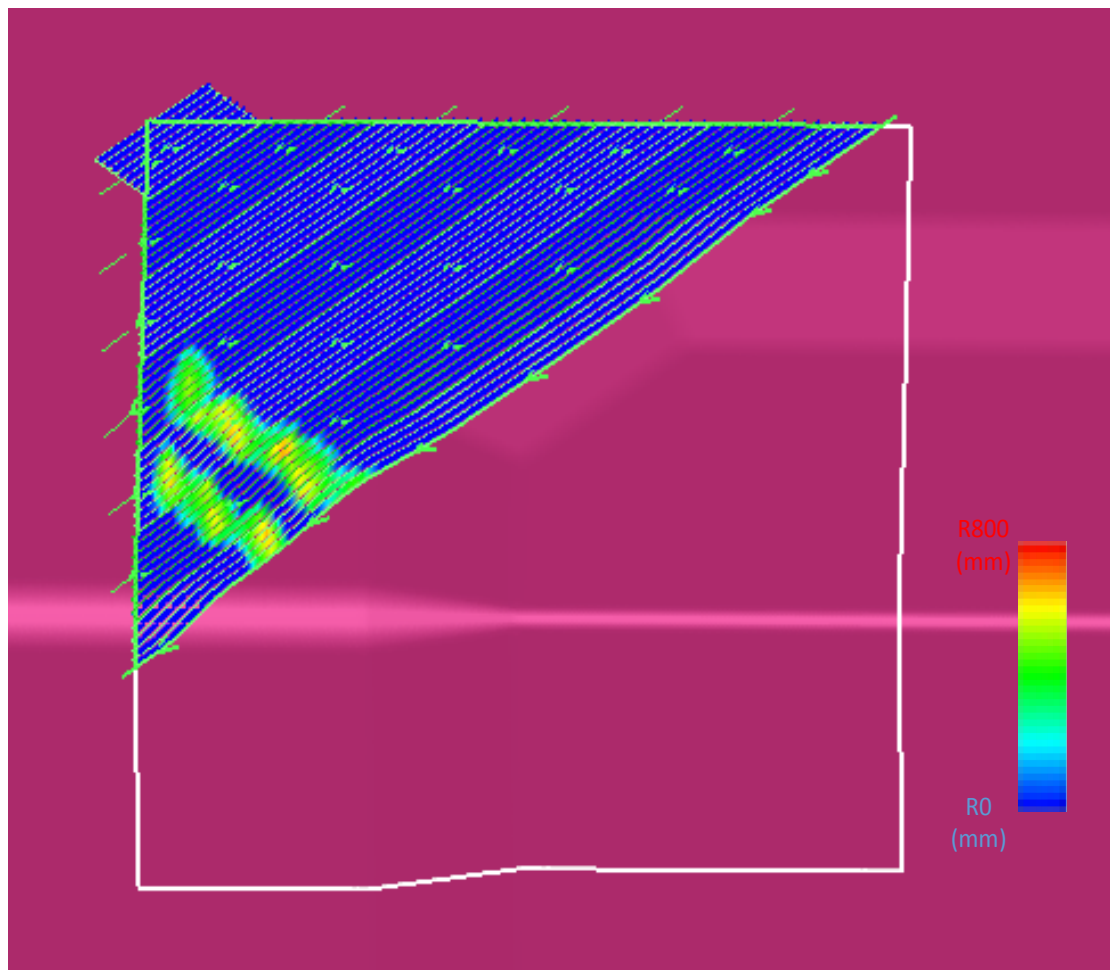


Figure 75: Custom trajectories for upper half of the 45 degree ply (steered either side of geodesic feature)

The lower sector is very similar to the upper sector, with a standard offset of the central sector being used to generate the remaining ply coverage. This is illustrated in Figure 76. The lower sector also contains a tape extension near the corner to mitigate the likelihood of a short tape lifting off the tool surface due to the material spring overcoming the material adhesion.

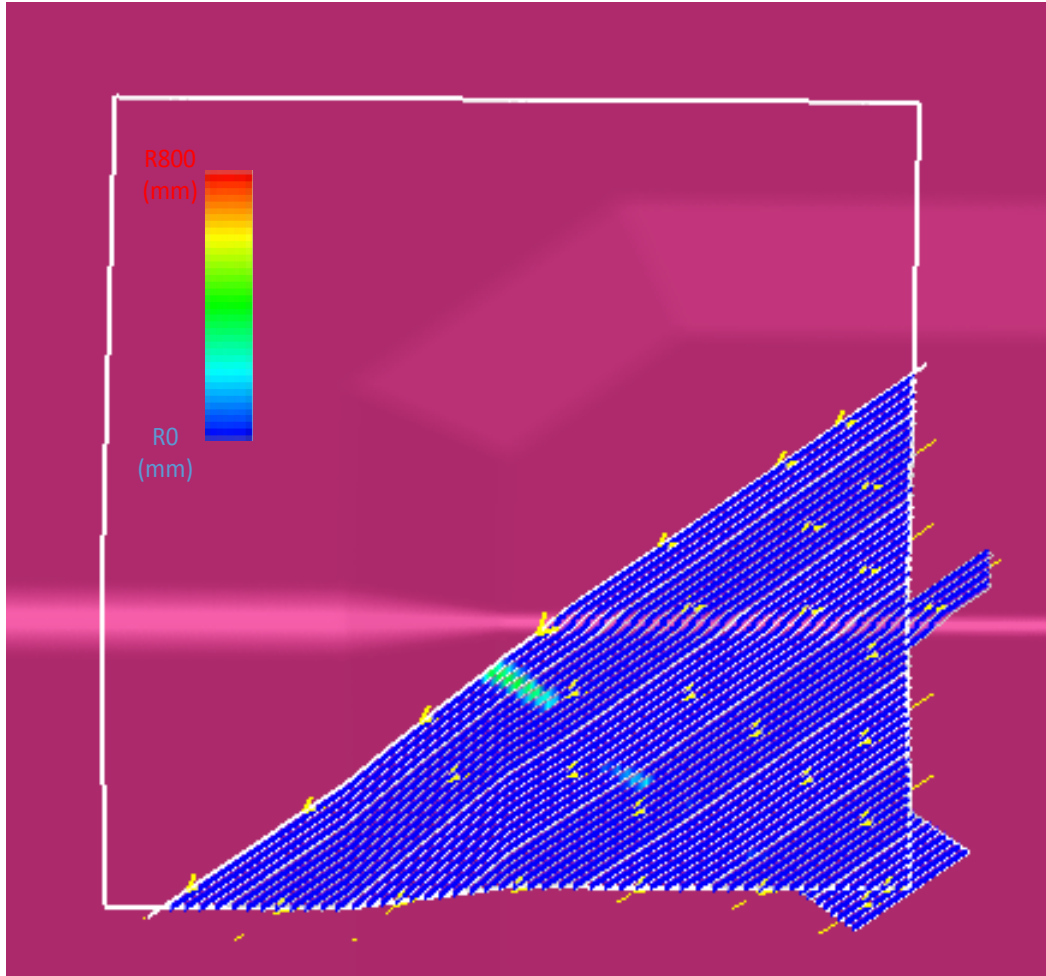


Figure 76: Custom trajectories for lower half of the 45 degree ply (steered either side of geodesic feature)

The manufactured 45 degree ply using the customised fibre trajectories is scanned using a contactless portable CMM scanning arm. The metrology verification checks that any defects caused by fibre steering are acceptably small. The scan result is shown in Figure 77, proving that the customised fibre trajectories can spread the unacceptable steering induced defects into smaller acceptable defects over a longer length of fibre trajectory.

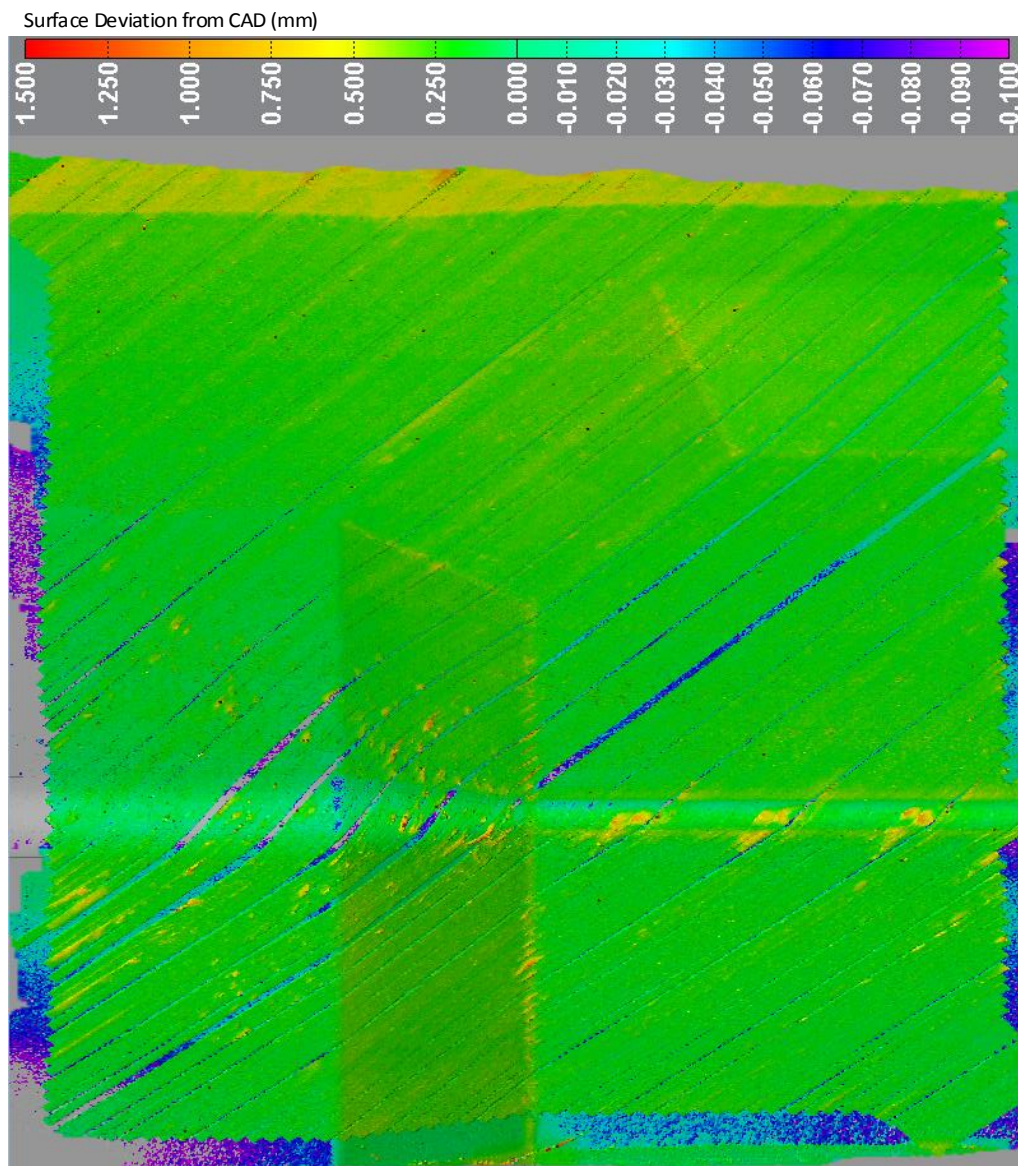


Figure 77: Metrology scan of first 45 degree ply using customised fibre trajectories. Gaps between courses can be seen coloured grey or blue.

The 45 degree ply that was manufactured as part of the programming testing is illustrated in Figure 78. The gaps between the courses designed to aid the delivery of resin to the highly consolidated regions can be seen in the photo.

Figure 79 illustrates the 135 degree ply which was programmed using the same customised fibre trajectory strategy as the 45 degree ply.

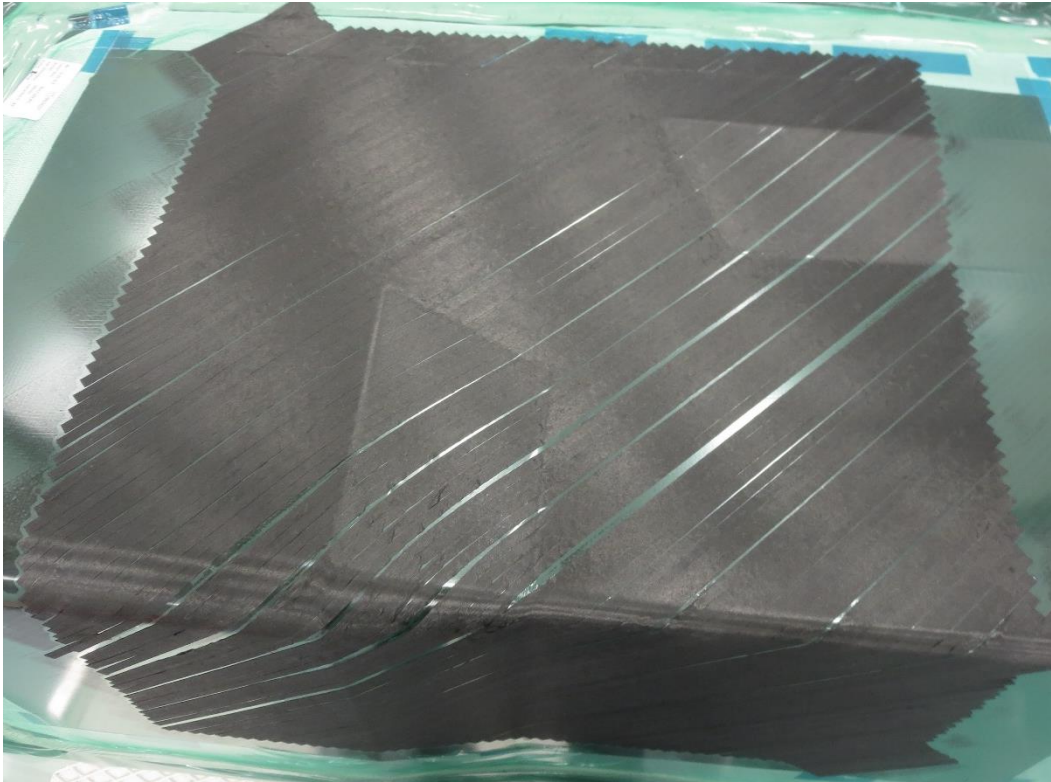


Figure 78: Photograph of 45 degree ply using customised fibre trajectories

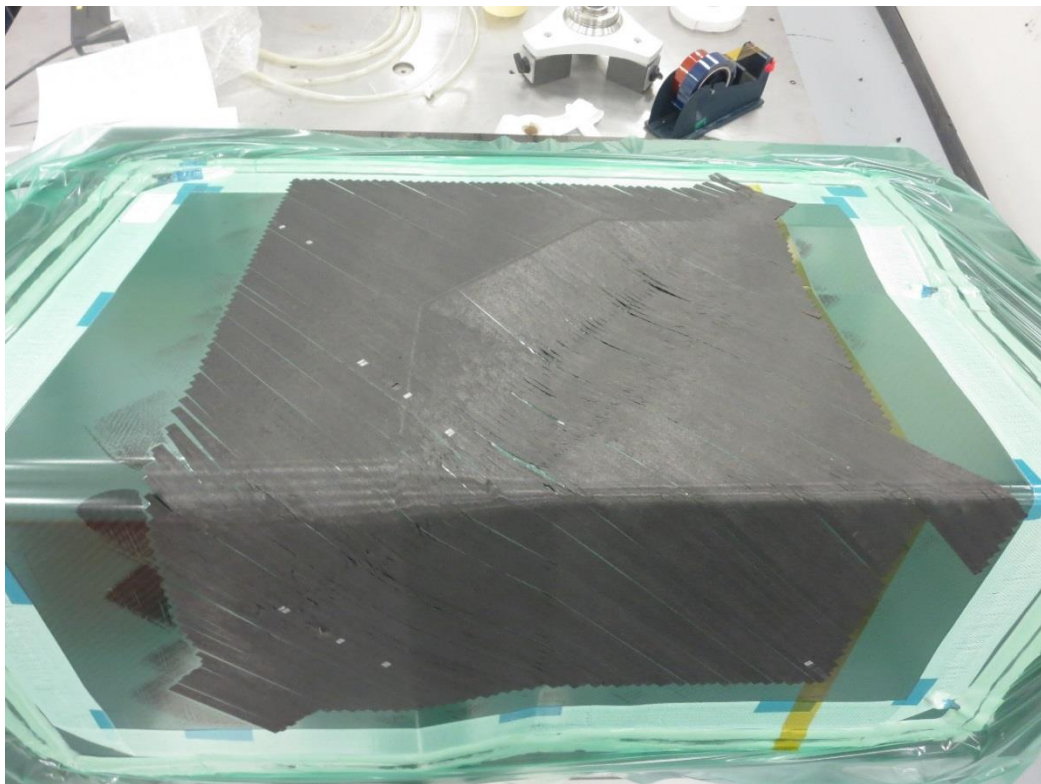


Figure 79: 135 degree ply using custom fibre trajectories

The design steps described in this sub-section for the use case prove that the manufacturing considerations from the generic design process can be used to generate acceptable ply coverage. The example validates the design process by generating a ply coverage that utilises fibre trajectories that are within allowable limits for gaps, overlaps and steering.

6.4.6 Consolidation and gaps

This section refers to the design process steps 24, 25 & 26 in Appendix A. The following manufacturing considerations must be accounted for in the detailed design:

- 1) Consider changing the geometry to reduce areas of high consolidation
- 2) Introduce gaps in the laminate to aid resin delivery during the infusion process

The design process steps 24 to 26 relate to the deliberate gaps that can be introduced into a laminate to enable it to infuse with resin more effectively.

6.4.6.1 Consider changing the geometry to reduce areas of high consolidation

The corner radius is the main area of high consolidation for the component. With the tight R10mm radius and a rapid increase in thickness around the pad-up, there is a requirement to increase resin flow to the radius, particularly the tapered radius section. The geometry in this location cannot be changed due to the original design intent, so the introduction of gaps into the laminate was used.

6.4.6.2 Introduce gaps in the laminate to aid resin delivery during the infusion process

By introducing gaps in between the courses, resin flow channels can be incorporated into the laminate at the design stage. The gaps deliberately designed into the 90 degree ply are illustrated in Figure 80.

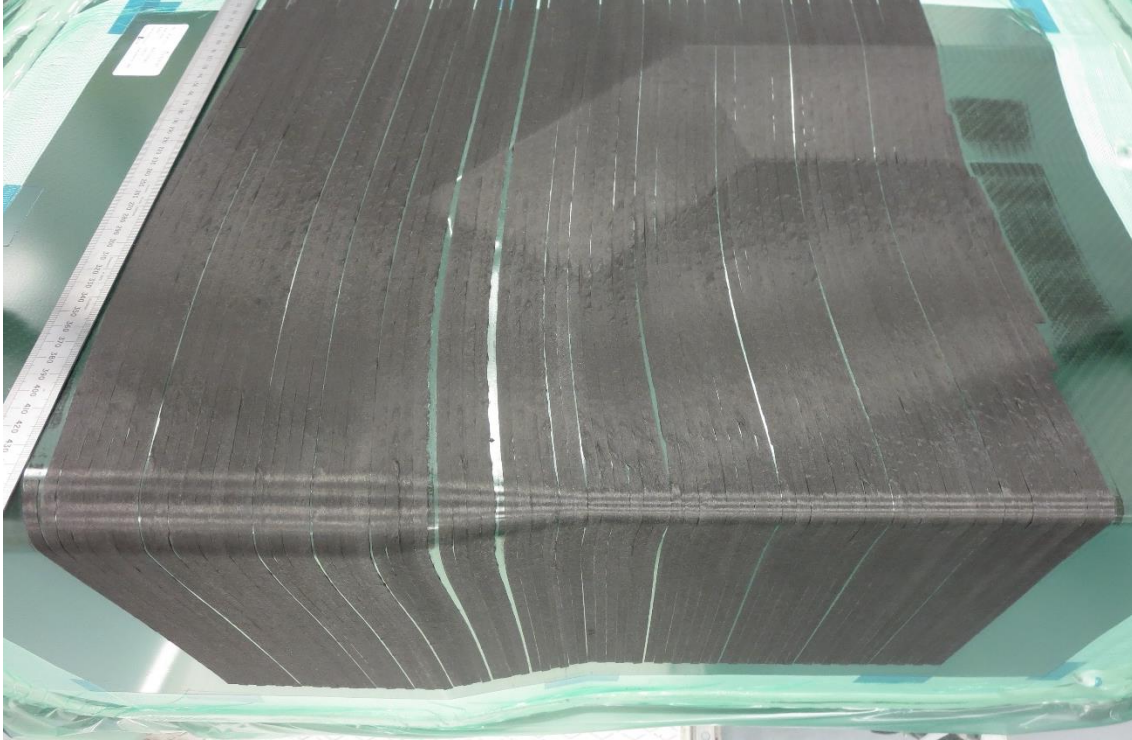


Figure 80: Steered 90 degree fibres with additional gaps on tapered radius

The gaps introduced into each ply act as resin flow channels. Without the gaps, the laminate becomes highly compacted on the radius of the component due to the reduced contact patch of the AFP deposition roller during layup of the radius. The high compaction force reduces the laminate permeability by compressing the trapped air in the material whilst the material binder is simultaneously activated by the AFP heating process. The gaps are larger in the areas of highest compaction, such as the tapered radius section. The gaps in the laminate of the use case help to validate the generic process by mitigating a resin infusion risk that would manifest in the later stages of the manufacturing process.

6.4.7 Manufactured part

In this section the 28 steps of the design process flow are concluded with the manufacture of the use case component. The successful layup of the component using the AFP process demonstrates that all of the critical manufacturing constraints associated with AFP have been incorporated into the design.

Table 27: Influence of the design process on the use case component

Design Action	Without Design Process	Influence of Design Process	Benefits
Section 6.4.1: Material thickness & thickness laws	Design mass and thickness is unrealistic.	Design can be manufactured from composite materials, but is 4% heavier than intended.	Manufacture from composite materials is enabled. Captured additional thickness can be included in the structural optimisation.
Section 6.4.2: Minimum cut lengths	Design can only be manufactured using manual hand layup.	Design can be manufactured using AFP, but is 10% heavier than intended.	Manufacture using automated process is enabled. Captured additional thickness can be included in the structural optimisation.
Section 6.4.3: Tool design	Tool design based on only the component would have required a bespoke tool stand.	Tool design was altered to use existing tool table.	Reduced cost of tooling solution.
Section 6.4.4: Axis system and fibre angles	Fibre angles deviate from design intent by up to $\pm 5^\circ$	Fibre angles adjusted to be within the allowed $\pm 3^\circ$ tolerance.	Fibre angles closer to design intent, and within design allowable.
Section 6.4.5: Steering of fibres	Without fibre trajectory steering, tapes would include defects.	Steering fibre trajectories enables defects to be reduced or eliminated.	AFP laminate produced with no unacceptable defects.
Section 6.4.6: Consolidation and gaps	Radius likely not to infuse with resin due to high compaction forces.	Resin flow channels introduced into the laminate to aid infusion.	Flow channels enable the resin to flow to the areas of poor permeability, increasing the chances of a successful resin infusion process.

Table 27 records how the design process has influenced the development of the use case component. The final laminated component is shown in Figure 81 and Figure 82. The thickest sides of the component are built up with layers of self-adhesive cork. The cork edge to the preform enables the AFP roller to compress and settle before making contact with the laminate. The practice leads to a higher quality laminate with fewer thickness variations and very repeatable positioning of the fibres.

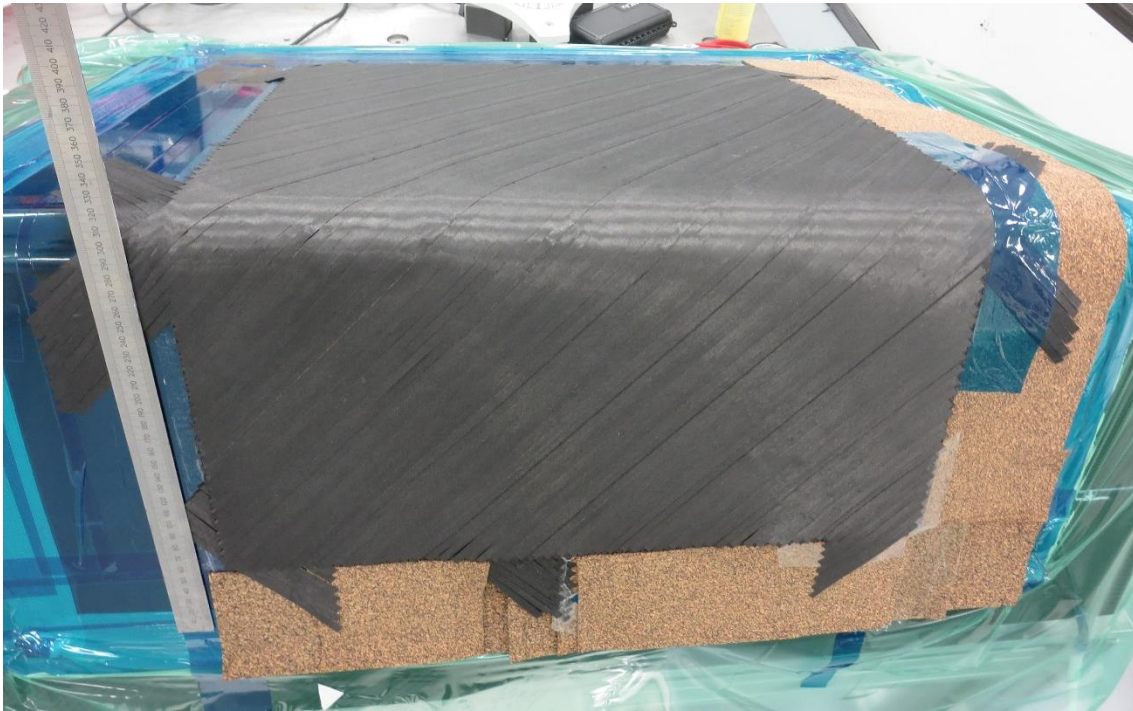


Figure 81: Photograph of use case demonstrator laid up as a dry fibre AFP laminate

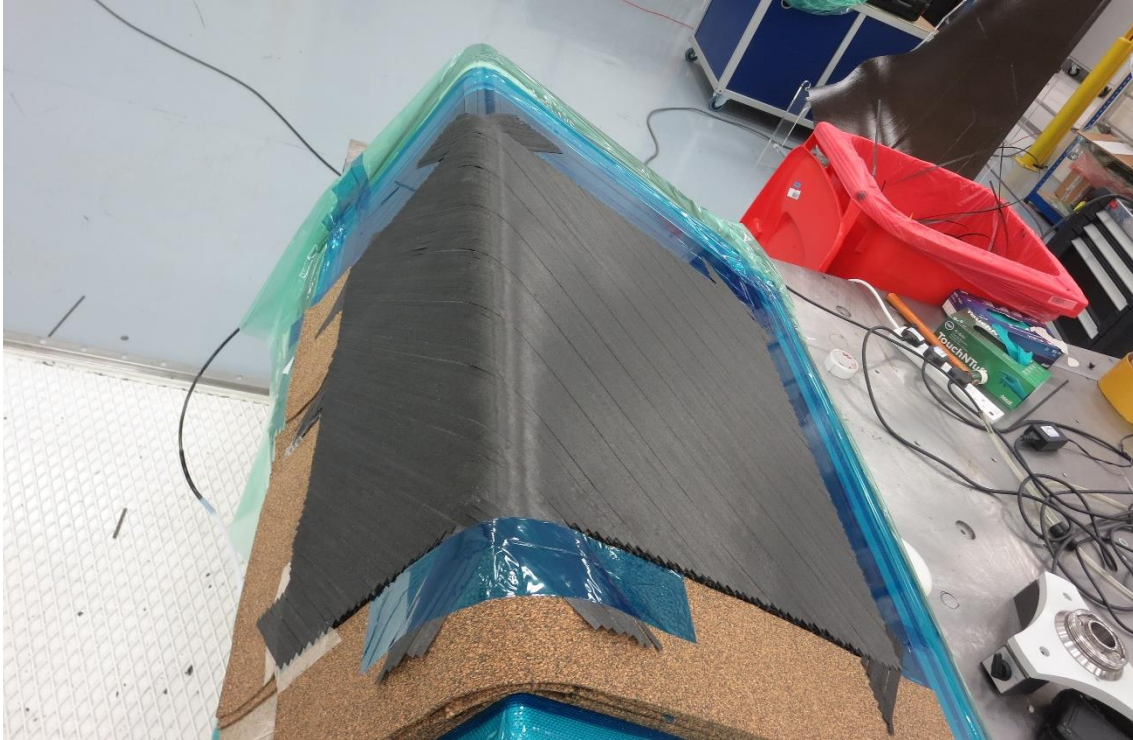


Figure 82: Photograph of use case demonstrator laid up as a dry fibre AFP laminate

The successful resin infusion process demonstrates that the concerns regarding the over-consolidated regions of the laminate have been mitigated at the component design stage. Figure 82 illustrates the use case component after the final ply has been laminated. The recess in the tool has now been fully filled with material to provide a flat exterior profile.

6.5 Concluding remarks

In this chapter the six sub-sections of the use case have been described and demonstrated using an industrially relevant example. The design started with only component performance objectives, but by following the design process steps, the additional automated manufacturing process constraints have been systematically applied to the design with respect to the original design intent. The resulting component is compromised in some areas such as mass and fibre volume fraction directly as a result of the manufacturing process constraints.

The design step in section 6.4.1 addressed the design rules around thickness laws, stacking sequences and material thicknesses. The application of these

rules added 4% additional mass to the design, and would have been the same for both manual lay-up and automated processes. This mass gain is typical in industrial designs where design fidelity is increasing as a result of structural analysis.

The design step in section 6.4.2 addressed the minimum cut length requirement of the automated process. The shape of the plies in the laminate around the locally reinforced area were altered and the component mass was increased by 10% to account for a machine specific parameter. This mass can be directly attributed to the chosen manufacturing process and specific machine. The Coriolis machine selected has a MCL of 100mm, however a competitor machine may have a larger or smaller MCL which would offer a proportionally larger or smaller mass addition. This design penalty is a direct result of selecting an automated manufacturing process to produce the component, however identifying this extra mass before the structural optimisation has enabled the extra mass to be taken into account when evaluating the performance of the component.

The design step in section 6.4.3 did not require the component design to be altered, but did lead to a second iteration of tooling design. The design process prompted this tooling check at a point in the design lifecycle where changes to the component and tooling design could be easily incorporated at low cost. If this step was addressed later in the design lifecycle then the cost of making the change could have been greater. The cost would have been significant if the component design and tool design had already been released for programming and manufacture.

The design steps in sections 6.4.4 and 6.4.5 did not add mass to the component, but did affect the orientations of the fibres. Typically the design allows the manufacturing process to deposit fibres within $\pm 3^\circ$, however some of the fibre trajectories were adjusted locally up to $\pm 5^\circ$ in order to reduce defects. The resulting fibre angles need to be captured in the early stages of the design so that they can be evaluated along with the extra mass to ensure that the component can still meet or exceed its performance objectives.

The design step in section 6.4.6 introduced gaps in specific areas of the laminate where high consolidation forces cause the laminate to exhibit locally poor permeability. These gaps ensure that the laminate can be successfully infused with resin, but alter the resin to fibre volume fraction, lowering the percentage of fibres per volume and reducing the structural performance of the laminate. This is an essential design modification required for dry fibre AFP preforms that rely on the resin infusion process to add the resin. There are other infusion processes such as RTM which would not be so sensitive to permeability, however liquid resin infusion is seen as a low-cost manufacturing technology and is currently dominating the industrial research in composite structures for most UK based aerospace structures companies.

7 DISCUSSION AND CONCLUSIONS

This chapter provides the reader with a detailed analysis of the research achievements of this work, whilst describing the quality, generality, and applicability of the methods followed. This is followed by a description of the key limitations to the research in section 7.3 and the suggested future work in section 7.4. This chapter is closed with a conclusion containing a summary of the work presented in this research.

7.1 Research achievements

The research reported in this thesis presents a new design process for incorporating manufacturing considerations into a composite component design. The aim of the PhD is to create “a generic design process to support the design for automated manufacturing of composites components”. By implementing the design process, DFM for automated manufacturing of composites can be systematically applied to the design lifecycle, providing engineers with a more reliable and repeatable way to create robust composite designs.

The research objectives defined in section 1.3 led to a number of research challenges around the identification of manufacturing constraints, where in the design lifecycle to account for them, and how to integrate them into existing digital tools. The achievement of the research objectives is recorded in Table 28.

Table 28: Achievement of research objectives

Research Objective	Chapter	Description
1: LITERATURE REVIEW	2	Literature evaluated for design and manufacturing of composites, DFM for composite structures, digital tools for DFM and systematic approaches to apply DFM
2: CAPTURING CURRENT PRACTICES USING INDUSTRIAL USE CASES	3	Three industrial examples demonstrated with use cases: Section 3.3.1 describes the structural sizing of a composite structure. Section 3.3.2 describes the manufacturing analysis carried out on a composite design including design rules. Section 3.3.3 describes the design evaluation methods including how to score the manufacturability of the design.
3: STRATEGIES TO APPLY DFM USING DIGITAL TOOLS	4	An approach to using digital tools (CATIA, Excel, VBA, C++ and AFP simulation software) to apply DFM is demonstrated with three industrially relevant use cases: Section 4.3 demonstrates low fidelity design evaluation. Section 4.4 demonstrates higher fidelity evaluation using simulation. Section 4.5 validates the proposed strategies by manufacturing physical trials.
4: DESIGN PROCESS AND SUPPORTING TOOLS FOR DFM	5	The design process is described in section 5.4. To demonstrate this three examples are described in sections 5.6, 5.7 & 5.8. The design process for AFP is described in 5.4.5.
5: VALIDATION OF PROPOSED DFM PROCESSES AND TOOLS	6	The final validation of the research is achieved using an industrially relevant use case, with the key DFM practices and tools described in chapter 6.

In addition to the achievement of the research objectives, the design process proposed is assessed for its quality, generality and applicability.

7.1.1 Quality of research process

To ensure adequate quality of the key findings derived from this research, a systematic approach to identifying and understanding the findings was established. Interactions with the experts referred to in this work were planned in advance so that each expert was able to understand the questions before the meeting or workshop took place. This ensured experts had time to think about their responses and offer examples to aid in the extraction of knowledge or add to the context of how a potential answer was used. All of the experts referred to in this work interact on a regular basis with the author, increasing the opportunities for them to be engaged with the research, and making the facilitation of more formal interactions much easier.

The author has gained experience in the aerospace industry working with different manufacturing and design projects. These projects include a variety of tasks that are relevant to this research such as developing design rules for the AFP process, creating digital tools to perform DFM at early stages in the design lifecycle and designing and manufacturing composite structures using automated deposition. Because the experience is relevant to the research objectives of this thesis, the experience enhances the quality of the research.

The reliance on use-cases to describe DFM and evaluate DFM throughout this research has enabled a strong theme of applied research to be implemented. The research has been fully industrially funded and many of the research findings have already been adopted by the sponsoring parties. The requirement to demonstrate research findings with real designs, real components and using existing digital tools enables real challenges to be described and addressed in each chapter. The use cases provide a step by step route to validation of each research objective or research finding. The final use case described in section 6.4 provides a validation of the full design process with an industrially relevant

component that is designed with the intention of highlighting known challenges associated with dry automated fibre placement manufacturing.

The assessment of each research objective, excluding the first objective relating to the literature review, was realised through quantitative and qualitative analyses. The quantitative analysis aimed to determine the validity of the results by means of measuring the design changes resulting from the integration of manufacturing constraints. In each chapter at least one use case was chosen to help qualify the research result. The qualitative analysis was carried out by using experts to assess the design and manufacturing objectives for each design process step. The experts help to establish the level of understanding of the design and manufacturing rules, and the use cases enable a secondary evaluation of usability and relevance of the design process. The procedure followed to validate the outcomes of this research is described in Table 29.

Table 29: Validation of the research outcomes

Objective	Validation	Description
2: CAPTURING CURRENT PRACTICES USING INDUSTRIAL USE CASES	Qualitative and Quantitative	The use cases are used to describe the typical problems faced by engineers in the aerospace industry. The data presented quantifies the design differences between as-designed and as-manufactured solutions.
3: STRATEGIES TO APPLY DFM USING DIGITAL TOOLS	Qualitative and Quantitative	The strategies described are derived and assessed by experts, providing quality assessment. The data presented in the use cases is used to quantify the impact of digital tools being used to apply DFM.
4: DESIGN PROCESS AND SUPPORTING TOOLS FOR DFM	Qualitative	The design process is heavily reliant on the quality assessments by a group of experts. The assessment is recorded in the table in section 5.4.5.
5: VALIDATION OF PROPOSED DFM PROCESSES AND TOOLS	Quantitative	The use case described in this chapter uses the design process to highlight manufacturing driven changes in the design and quantifies the effects of these changes in terms of mass gained by the component and manufacturing speed implications.

7.1.2 Generality of the research methodology

The generality of the research methodology is quantitatively discussed here. The field of DFM is wide and covers many different manufacturing processes, however this research focuses only on composite structures and automated production technologies. Generality can therefore only be achieved within some bounding limitations. The author believes that the design process proposed represents a generic approach that is common for many manufacturing processes, and can therefore be applied in a number of alternative contexts and in other industries. However, safe claims can only be made when they have been

validated with a suitable use case, so the generality of this research needs to be constrained as follows:

- Limited to the aerospace industry, or others using automated composite manufacturing technologies such as wind energy.
- Only valid for products where the full design lifecycle is accessible, not fully applicable for manufacturers who are not responsible for the conceptual design of the product.
- Only effective when adequate manufacturing and design expertise is available to carry out the assessment.

This research proved to be an effective way to ensure that an aerospace inspired composite component could be adapted to suit manufacture using an automated system. Further research is required to prove the success of the design process over a wider scope.

7.1.3 Applicability of the proposed design process

This section discusses the application of the design process and the potential business impact. The design process allows engineers to address manufacturing requirements of the design at the earliest possible stages in the design lifecycle, and as highlighted in section 1.1, when 80% of the manufacturing costs are fixed at the early stages of the design lifecycle [6], identifying these requirements early can lead to significant cost savings.

The aerospace industry is leading the drive to industrialise automated production methods and the extensive use of composite materials in aircraft structures. Some of the research carried out in this work has already been adopted in industry, and the exact nature of these adoptions is described in Table 30. For example, Airbus integrated the ply continuity methodology into the manufacturing ply design analysis tool named mPDA.

By taking a systematic approach to implementing design for manufacture, a company can ensure that composite designs are progressed into production with minimal design evolution and minimal production costs. In order to implement the design process described in chapter 5 for a current aerospace component and

production process, the FMEA analysis would need to be revised to take account of the specific automated deposition machines selected and the CAD system selected for the design. A team of experts would be required to assess any new process steps that the new software and new production system introduce. Because the design process is likely to remain subtractive, and the manufacturing process will still be additive, the majority of the process steps should remain unchanged, albeit with updated parameters such as minimum cut lengths to suit the new machines.

In summary, with this aerospace end-application in mind, the design process is sufficiently generic to be easily adapted to a new machine or a new design. The business impact will depend on the level of expertise available, but will in all cases act as a guide to evaluate the design with respect to the manufacturing process.

Table 30: Adoption of research in industry

Research Adopted	Customer	Section	Description
Ply Continuity Score	Airbus	Section 4.3 Section 4.4 Section 4.5	The ply continuity score has been integrated into the mPDA tool. This is used by Airbus to score composite wing designs for manufacturing prior to starting a detailed design.
Ply Complexity Score	Airbus	Section 3.3.3 Section 4.3.2 Section 4.4 Section 4.5	The ply complexity score has been used to support concept selection for composite fuselages, but has not been integrated into any baseline tools.
mPDA Design Rules	Airbus and NCC	Section 3.3.2 Section 4.5	The mPDA tool is used by Airbus to convert sizing data from a structural optimisation tool called ComBox, into CAD models whilst automatically applying the basic design rules and generating a ply continuity score. It will be used until the sizing process changes from subtractive to additive. The NCC also use mPDA to quickly generate CAD models of simple trial panels.
FMEA Design Analysis	NCC	Section 5.3 Section 5.4	The FMEA approach to analysing a design for manufacturing has been used for two research programmes at the NCC. The validation use case describes in this thesis is one of the examples.
AFP Design Process	NCC	Section 5.4 Section 6.4	The AFP design process generated as a result of this research is now used as the baseline design process flow for new AFP component designs at the NCC.

7.1.4 Achieving the research objectives

Each of the research objectives has been achieved in a separate chapter of this thesis. Table 31 draws comparison between each research objective and how it has been achieved in this thesis.

Table 31: Research objectives and descriptions how they have been achieved

Research Objective	Achievement
1. Capture the state of the art for DFM of composites using digital technologies.	Comprehensive literature survey of published research completed and reported in chapter 2.
2. Capture the current industrial design practices using use cases for composite structures.	Industrial design practices are explained and documented using the examples provided in chapter 3.
3. Develop strategies for applying DFM best practice through the use of digital tools.	Strategies for evaluating manufacturability are described and examples are given in chapter 4.
4. Develop a generic process and supporting tools to systematically apply DFM for automated composite manufacture.	A generic process is described in chapter 5, and the process is applied to the design of a composite component as an example. The supporting tools are described.
5. Validate the proposed DFM tool kit using a design use-case described in section 1.6 “Research Methodology”.	An industrially relevant use case is designed and then manufactured to validate the generic design process developed in this research. This is documented in chapter 6.

The use cases described in this research have been developed over six years, with some of the methods taking up to 18 months to create, test and refine. The key contributions are summarised in Table 32.

Table 32: The main research contributions, use cases and associated timescales

Contribution	Use Case	Timescale
Chapter 2: Design Rules	The industrial practice provided a source for the generic composite design rules. How the rules work with a subtractive sizing process and automated manufacture needed to be established.	Initial research into how the design rules affected the sizing and manufacturing processes started in 2011 and after 6 months of testing on a wing design the main issues had been identified.
Chapter 3: Ply Continuity	The concept of checking cells in an array for material occupancy and adjacency using a programmable procedure to generate a score for a given design.	A proof of concept was created in Excel based on an attempt to predict machine paths without CAD data. This was then developed into the first mPDA application over 9 months. mPDA went on to be further developed over 3 years.
Chapter 3: Ply Complexity	The concept of comparing the area of a ply with the circumference to generate a score for a given design.	The concept was created to account for geometry where ply continuity couldn't. This took 3 months to develop and test using an aircraft wing as a use-case.
Chapter 4: AFP Simulation	The use of AFP simulations to generate indicative cycle times. The strategies required to steer fibre trajectories to eliminate defects.	The coupons simulated and manufactured in chapter 4 took 6 months to design, simulate and manufacture. The methodology to create custom steered fibre trajectories was developed over 18 months with over £600k worth of trial components manufactured.
Chapter 5: FMEA Process	The adaption of the FMEA process to create a generic design process.	Developing the methodology and testing it on trial components took 6 months.
Chapter 6: Final Demonstrator	The design, development and manufacture of the use case using the generic design process.	The design, development and manufacture of the use case took 15 months and cost approximately £400k.

7.2 Novelty

In section 2.7.3 the research gap was identified in three main areas:

- 1) a lack of manufacturing constraints being addressed in the early stages of the design lifecycle,
- 2) a shortage of research verified with physical use cases, and
- 3) the need for methods to design for automated production techniques.

The novelty in this research is the way in which each of these three gaps have been addressed.

Lack of manufacturing constraints in the early stages of design. The generic design process demonstrated that the adapted FMEA process was capable of identifying the manufacturing constraints relative to the steps in the design process, and provided a mechanism to account for the constraints at the earliest opportunity in the design lifecycle. The methods used to define the design process and identify the manufacturing constraints addresses this research gap.

Shortage of research verified with physical use cases. The research objectives in this thesis utilise a number of design examples and use cases for illustration purposes. This provides an opportunity to validate a number of design steps and manufacturing constraints with physical components. Since the automated deposition technology is not abundantly available to research institutions, and is very costly to operate, very few automated deposition research articles conclude with a physical demonstrator as validation. This research has been carried out with unlimited access to three AFP machines at the NCC, and access via industrially funded research to a further four alternative types of AFP machine. Hence, multiple physical demonstration components have been manufactured to validate the research objectives, and address the research gap.

Requirement of methods to design for automated production. The challenge of designing for automated composite manufacturing processes was barely recorded in published literature. Many machine specific rules must be established

for any given design, but the interpretation of the rules remains the responsibility of the designer and is dependent on the experience gained by the individual. The generic design process described in chapter 5 and the strategies for applying DFM in chapter 4 enable a designer to adopt a systematic approach to applying manufacturing constraints to a design, without relying on previous experience to define the correct practices. The approach is suitably generic to be applied to a design when the specific deposition machine is not known, yet detailed enough to be used with machine specific constraints. This approach was not reported in published literature, and now it has been defined, it addresses the remaining research gap.

7.3 Key research limitations

In this section the limitations related to the research results are described. Three types of limitation have been identified. The first limitation addresses the availability of expert knowledge. The second limitation addresses the complexity of the design, and the third addresses the suitability of the manufacturing technology selected. In each of these limitations, the compromise between design performance and production performance is traded and an unsatisfactory result may emerge if the trade-off between the two is not balanced:

- **Availability of expert knowledge:** As previously mentioned, the design process is highly dependent on experts being able to identify potential manufacturing problems, and also identify the root cause of the problem in the design. In this research the design process and manufacturing process were very well understood by the experts, so they were able to propose evidence and experience based analysis. This led to the formation of 28 high integrity design process steps. If the manufacturing or design process is new or novel, and experience with previous manufactured components is not readily available, then the correct manufacturing constraints may not be easy to identify and their root cause may be overlooked.
- **Design complexity:** A high performance, high complexity design may have less room for adaption when it comes to incorporating changes to

suit the manufacturing process. In section 6.4.2, the shape of the use-case component changed, adding 10% additional mass to the component in order to account for a machine characteristic, yet the original design could have been manufactured without these changes if a manual process had been chosen for production. This highlights the limitation that designing for automated production requires a large degree of design freedom, and some complex composite structure designs cannot tolerate such significant changes.

- **Manufacturing suitability:** The design process assumes that the manufacturing process is suitable for the design. In some cases, a technology like AFP is not appropriate for the specific design intent, and the benefits of an automated and repeatable manufacturing process do not outweigh the design limitations that need to be accounted for. In these instances, the design process is likely to highlight all of the manufacturing constraints, but the resulting design may fail to meet its original performance criteria. This is common with components that are manufactured by hand and are not sensitive to manufacturing variation. Examples are sports equipment like bicycle frames and tennis rackets, compared to the example of an aerospace engine fan blade where part repeatability is more critical than component mass.

7.4 Future work

This section lists research areas that have been identified by the author as having potential to carry out further work:

- **Knowledge management.** A more structured way to store the knowledge captured by experts while evaluating the design process would help the re-use of captured expert knowledge. Being able to network the knowledge and visualise trends could make the creation of new rules easier.
- **Alternative manufacturing processes.** Further work is required to expand the design process so that it incorporates alternative automated manufacturing processes and materials. Automated tape laying, braiding

and filament winding are all automated processes that could be represented with minimal additional work.

- **Multi-objective optimisation.** Throughout this thesis, the conflicting requirements of design performance and manufacturing performance have been compared. The mechanisms to evaluate and numerically score performance parameters, such as mass and stiffness for design, and ply continuity and ply complexity for manufacturing already exist, and can therefore be used as objectives for a multi-objective optimisation exercise. For example, changing the sequence of ply orientations in all of the individual cell stacking sequences in order to reduce mass and improve ply continuity would make a valuable digital tool for DFM.
- **Manufacturing informatics.** The recent developments in digitally connected manufacturing systems enable the use of manufacturing process simulation to be more readily used to influence the design and predict manufacturing process changes. The modern manufacturing systems also monitor the processes at higher fidelity and gather large amounts of data about the process that can be used to enhance understanding of the process mechanics. Further work is required to understand how the design process can be improved to utilise the benefits of higher fidelity process data and process simulations.

7.5 Conclusions

In this research, a generic process that uses digital technology to facilitate design for automated manufacture for composite structures was developed. The design process addresses a set of industrial needs identified by the author. The parts of this PhD thesis related to the original industrial motivations are:

- **Digitise manufacturing constraints so that they can be used with digital tools.** The Airbus MDOW project [11] identified a need to represent manufacturing at a much earlier stage in the design lifecycle than would normally be considered best practice. This introduced the challenge of modelling high fidelity manufacturing events using very low fidelity design data. In this regard, a key feature that was developed as part of this work

is the methodology of the ply continuity and complexity scores. The methods described in this work have been incorporated into the digital tools used by Airbus to evaluate conceptual and preliminary composite aircraft designs.

- **Establish processes that represent manufacturing considerations at early stages of the design lifecycle.** It is easy to retrospectively assess the decisions made early on in the design lifecycle when faced with a very mature design or a physical component. However, making high integrity design decisions about the manufacturing process when the design fidelity is very low is a serious challenge. This research intended to create a systematic approach to evaluate the design lifecycle with respect to manufacturing. The work demonstrated that a designer equipped with a low fidelity design could follow basic design process steps to identify how design decisions will influence the manufacturing process. The final use case proved that this approach could be taken to mature a conceptual design and ensure it could be manufactured using an automated deposition process.
- **Improve the manufacturing speed through design.** The industrial goal behind applying DFM best practices for automated composite production is to manufacture a high performance aircraft with a large profit margin. If Airbus decide to replace their current A320 family of single aisle aircraft with a composite variant, they will need to offer the airlines an aircraft that is capable of a significant performance improvement, at a price that is competitive with the existing aircraft family and with a similar profit margin. In order to achieve this, the next generation aircraft will need to be designed with an automated composite manufacturing process in mind. Manually producing composite structures using lower cost labour was ruled out because manual lay-up could not deliver the repeatability of an automated system. This research identifies a number of tools that can be used to indicate the manufacturing speed of a design, and it also highlights the points in the design lifecycle where it is important to account for the manufacturing process constraints.

- **Advance the understanding of DFM for automated composite manufacturing.** Until undertaking this work, the active steps taken by a designer to address the AFP manufacturing constraints had not been adequately recorded or reported. A good designer or programmer relied on their own past experience to identify best practice, and the outputs from different designers varied based on their experience making it difficult to achieve consistency across designs. Capturing the manufacturing intelligence in the form of a process flow with corresponding corrective actions provides designers with a generic process to follow that contains both the manufacturing constraints and the corresponding design actions in a chronological sequence of steps. This design process has been reported in this thesis, and also published for use at the NCC and Airbus.

The validation of the design process was achieved through the successful design and manufacture of a demonstrator component. The design lifecycle has been documented in this work, and most significant DFM steps have been described in greater detail in chapter 6. The manufactured component satisfied the original design performance requirements, but mass was added in order to satisfy the requirements of the manufacturing process. The design process has proven to be an adequate guide for the application of automated composite manufacturing considerations throughout the lifecycle of a composite structure design.

Prior to the initiation of this research, the following industrial challenges were unresolved in the published literature:

- Whilst systematic approaches to apply DFM to a design have been published, a solution to address the specific challenges of automating composite manufacturing had not been developed.
- The challenges of designing for automated composite manufacture are not adequately addressed in existing literature and industrial design guides, relying on the skill and experience of the individual designers to produce high quality designs.

As a result of this research, the following new conclusions have been generated:

- A systematic design process can now be used for composite components that will be manufactured using automated production technologies.
- The specific manufacturing constraints which must be mitigated in order to use automated composite manufacturing are known.
- The design lifecycle for composite structures which will be manufactured using AFP is now understood, with the key manufacturing considerations identified at the correct stages of the lifecycle in order to have maximum effect.

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APPENDICES

Appendix A Individual design steps evaluated using FMEA method

The following design steps have been analysed using an FMEA method. The design process flow from chapter 5 is used as it takes a low fidelity preliminary concept for a composite laminate through to a design with sufficient fidelity to begin manufacture using an AFP machine.

A.1 Check integrity of surface

Design Step: 1

Design Phase: Concept

Task Objective: Check integrity of surface

Task Description: Offset surface by 0.2mm

Design Objective: Successfully test surface integrity

Manufacturing Objective: Prove ply offsets will work in downstream processes

Failure Mode: Surface fails to offset

Effect(s) of Failure: Design cannot be progressed without surface repairs

Root Cause: Surface continuity inadequate, typically as a result of generating surfaces from CFD data

Design Severity: High

Manufacturing Severity: High

Corrective Action: Reject surface, do not proceed

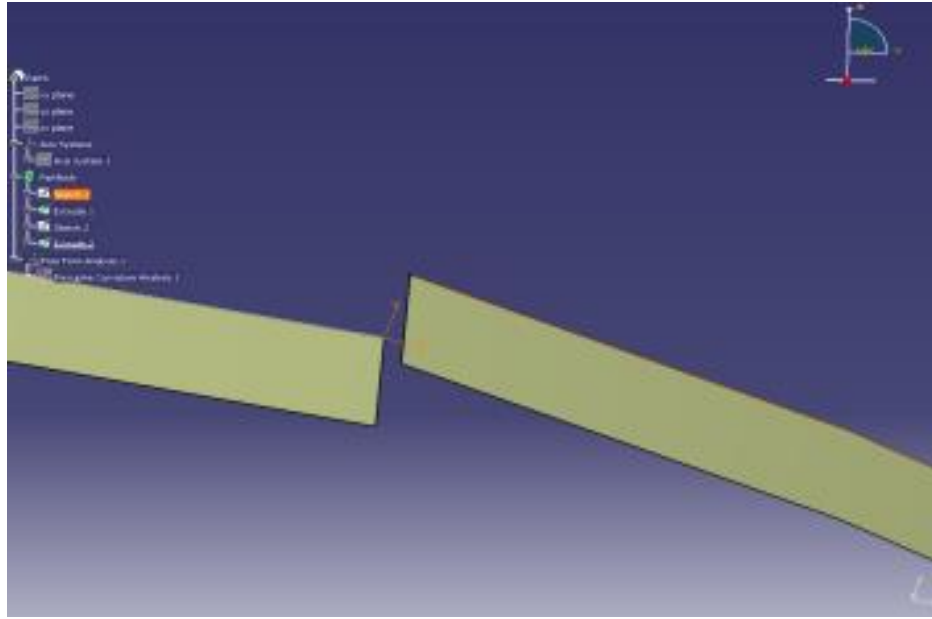


Figure A-1: Illustration of a typical gap between two surfaces

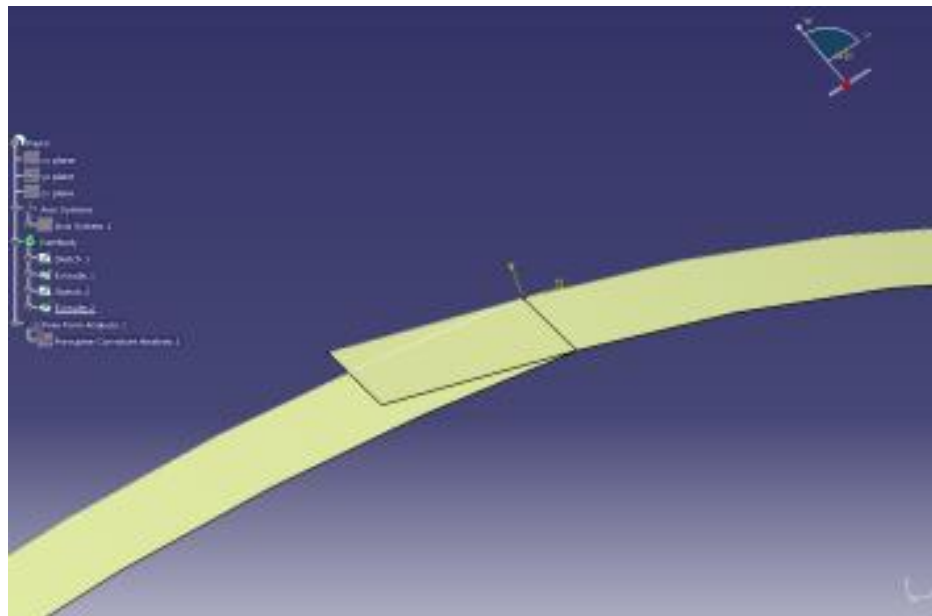


Figure A-2: Overlap of a surface, causing surface offset failure

A.2 Check integrity of surface

Design Step: 2

Design Phase: Concept

Task Objective: Check integrity of surface

Task Description: Apply extended ply boundary

Design Objective: Successfully test surface integrity

Manufacturing Objective: Check that surface doesn't have unplanned holes or gaps

Failure Mode: More than one boundary generated

Effect(s) of Failure: Design cannot be progressed without surface repairs

Root Cause: Surface broken into multiple segments

Design Severity: High

Manufacturing Severity: High

Corrective Action: Fill surface, otherwise return and do not proceed. Extend surface by at least 200mm tangentially

A.3 Position rosette on surface at suitable seed point

Design Step: 3

Design Phase: Concept

Task Objective: Position rosette on surface at suitable seed point

Task Description: Install rosette in model. Geodesic extend each orientation to edge of surface

Design Objective: Ensure 0 degree and 45 degree axis are correctly orientated

Manufacturing Objective: See how far the fibre angle deviates when geodesically extended

Failure Mode: Location of rosette and seed point cause geodesic fibre deviation that exceeds specified limits

Effect(s) of Failure: Unable to deposit fibres on surface without introducing unacceptable defects

Root Cause: Geodesic fibre paths form the ideal defect free trajectories, but are diverted by complex geometries. If the seed point is poorly located, multiple complex geometries cause compounded deviations.

Design Severity: Medium

Manufacturing Severity: High

Corrective Action: If deviation is too great, consider alternative seed point to locate rosette if possible, otherwise return and do not proceed

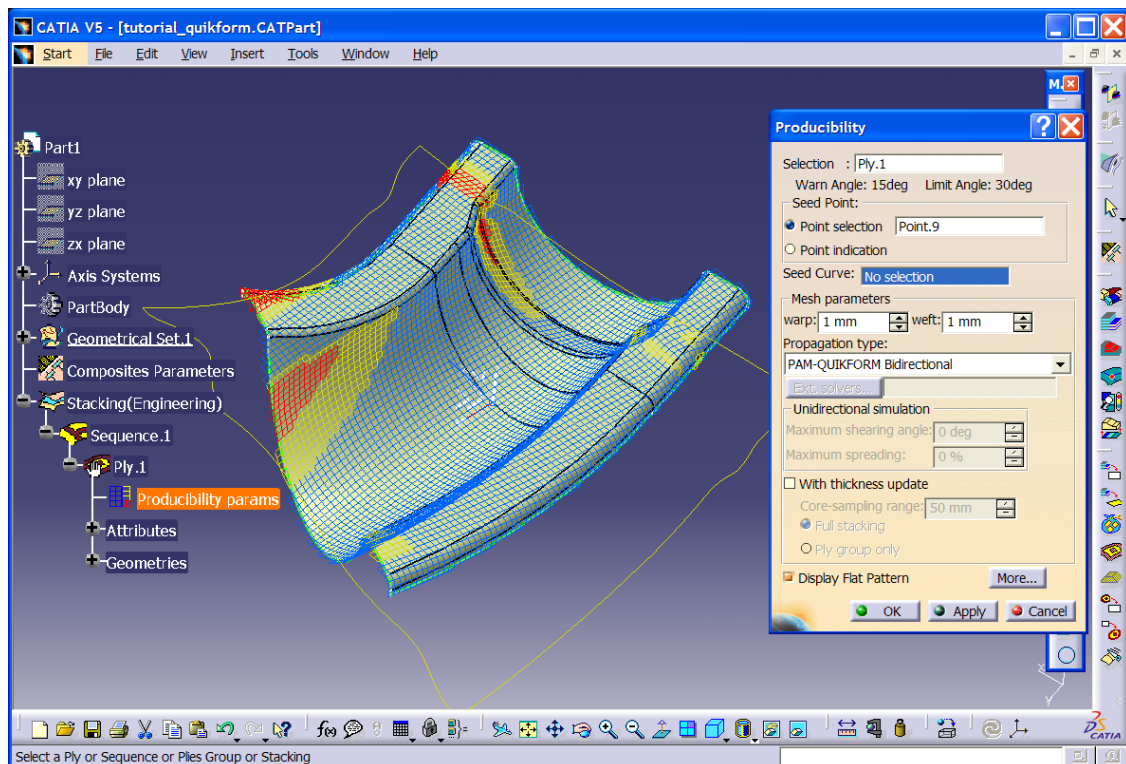


Figure A-3: Producibility analysis used to check the location of the rosette and seed point. Areas in red exceed the permitted angular deviation

A.4 Establish ply sequences

Design Step: 4

Design Phase: Sizing

Task Objective: Establish ply sequences

Task Description: Calculate ply sequence for each sized zone based on thickness law and thickness

Design Objective: Convert Thickness Law and thickness into a balanced stacking sequence (Minimum thickness)

Manufacturing Objective: Ensure manufacturing ply sequence rules are applied (results in added thickness)

Failure Mode (A): More than 3 layers of the same orientation are sequenced together

Effect(s) of Failure (A): Plies interlock and cause bridging or wrinkling upon material de-bulking

Root Cause (A): Plies with same orientation interlock and prevent inter-ply shear during cure or de-bulk

Failure Mode (B): 45 and 135 or 0 and 90 degree plies are not equal

Effect(s) of Failure (B): Laminate warps during cure

Root Cause (B): Un-balanced laminates cause residual stress. At least two perpendicular orientations should be balanced

Design Severity: High

Manufacturing Severity: Low

Corrective Action: Add plies (thickness) to satisfy manufacturing constraint

A.5 Evaluate ply shapes

Design Step: 5

Design Phase: Sizing

Task Objective: Evaluate ply shapes

Task Description: Transpose stacking sequences into individual ply shape maps

Design Objective: Create basic laminate definition to show which plies within a zone are continuous to neighbouring zones

Manufacturing Objective: Increase ply continuity

Failure Mode: Ply continuity score unacceptable

Effect(s) of Failure: Sub-optimal manufacturing solution

Root Cause: Excessive tailoring of the stacking sequences leads to poor ply continuity, as a result the deposition process is slowed down

Design Severity: High

Manufacturing Severity: High

Corrective Action: Re-sequence with alternative stacking sequences until ply continuity is improved. If stacking sequences have been provided instead of thickness laws, change sequence by maximum of 10% of thickness

A.6 Generate sizing evaluation score

Design Step: 6

Design Phase: Sizing

Task Objective: Generate sizing evaluation score

Task Description: Calculate the perimeter/area score for all ply shapes

Design Objective: Higher score indicates greater degree of continuous fibres in the laminate

Manufacturing Objective: Higher score indicates faster manufacturing process

Failure Mode: Ply continuity score unacceptable

Effect(s) of Failure: Sub-optimal manufacturing solution

Root Cause: Excessive tailoring of the stacking sequences leads to poor ply continuity, as a result the deposition process is slowed down

Design Severity: Low

Manufacturing Severity: Low

Corrective Action: Consider engineering stacking sequences to influence higher score

A.7 Convert 2D sizing to 3D sizing

Design Step: 7

Design Phase: Sizing

Task Objective: Convert 2D sizing to 3D sizing

Task Description: Map sizing data onto surface - establish grid in CATIA's eCPD workbench

Design Objective: Grid must closely match zone defining features of the sizing data

Manufacturing Objective: Zone boundaries should be clearly defined, preferably using intersecting simple geometry like planes

Failure Mode (A): Grid construction not suitable for propagating ply boundary support guides

Effect(s) of Failure (A): Without supports the ply boundaries cannot be generated

Root Cause (A): Sub-standard geometry used to configure composites grid elements. For example, planes can easily be offset to create a staggered ply boundary, but complex geometry can sometimes not be offset using geodesic or Euclidean functions

Failure Mode (B): Grid contains different number of cells to input array

Effect(s) of Failure (B): Ply definition does not load correctly

Root Cause (B): Transposition of 2D array to 3D grid does not match

Design Severity: Low

Manufacturing Severity: Low

Corrective Action: Grid integrity will not be tested until ply boundaries are generated later in the design process

A.8 Configure ramps and clearance parameters

Design Step: 8

Design Phase: Detail Design

Task Objective: Configure ramps and clearance parameters

Task Description: Set ply boundary rules (ramping rates)

Design Objective: Set exclusion zones where ramping should not occur - such as in interface areas

Manufacturing Objective: Restrict ramping rates as the angular changes cause changes in fibre direction and can restrict machine access

Failure Mode (A): Ramp geometry too steep for deposition roller access

Effect(s) of Failure (A): Deposition machine cannot access ramped areas

Root Cause (A): Angle of ramp causes roller to bridge preventing adequate consolidation of material

Failure Mode (B): Ply boundaries too close together

Effect(s) of Failure (B): Deposition slowed excessively to perform boundary cuts and starts

Root Cause (B): Ply boundaries are sufficiently spaced in the grid until the ramping rules move them

Failure Mode (C): Ply shapes fragmented

Effect(s) of Failure (C): Sub-optimal manufacturing solution

Root Cause (C): Excessive tailoring of the stacking sequences leads to poor ply continuity, as a result the deposition process is slowed down

Design Severity: High

Manufacturing Severity: High

Corrective Action: Change clearance zone and ramp rates and re-compute

A.9 Add laminate attributes to model

Design Step: 9

Design Phase: Detail Design

Task Objective: Add laminate attributes to model

Task Description: Import/enter sizing data into the grid definition within eCPD

Design Objective: Represent sizing data with minimal changes

Manufacturing Objective: Ply coverage should be as continuous as possible

Failure Mode (A): Uncured ply thickness not representative

Effect(s) of Failure (A): Deposition NC program causes either poor consolidation or collisions

Root Cause (A): The deposition program requires a revised surface to follow at 2mm layers in the laminate. If the revised surfaces are too low relative to the programmed surface the roller does not consolidate the laminate, too high and the machine may collide with the laminate

Failure Mode (B): Orientation nomenclature incorrect

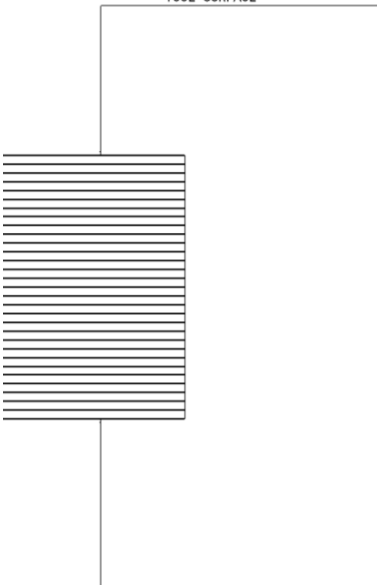
Effect(s) of Failure (B): Ply orientations transposed incorrectly

Root Cause (B): CAD material catalogue doesn't match sizing data material

Design Severity: Low

Manufacturing Severity: Low

Corrective Action: Re-check grid definition if import is not successful



SEQUENCE	PLY	ORIENTATION	MATERIAL	STAGGER (TOWS)	AFP GUIDE CURVE	COURSE TO COURSE GAP
SEQUENCE.1	PLY.1	0	0.25 CARBON	0	STD 0 GUIDE CURVE	1
SEQUENCE.2	PLY.2	0	0.25 CARBON	0	SLIT 0 STRAIGHT GUIDE CURVE	1
SEQUENCE.3	PLY.3	0	0.25 CARBON	0	SLIT 0 STEERED GUIDE CURVE	1
SEQUENCE.4	PLY.4	0	0.25 CARBON	2	PLY DROP GUIDE CURVE 1	1
SEQUENCE.5	PLY.5	90	0.25 CARBON	0	PLY DROP GUIDE CURVE 1	1
SEQUENCE.6	PLY.6	0	0.25 CARBON	2	90 GUIDE CURVE	1
SEQUENCE.7	PLY.7	0	0.25 CARBON	0	STD 0 GUIDE CURVE	1
SEQUENCE.8	PLY.8	0	0.25 CARBON	4	SLIT 0 STRAIGHT GUIDE CURVE	1
SEQUENCE.9	PLY.9	0	0.25 CARBON	6	SLIT 0 STEERED GUIDE CURVE	1
SEQUENCE.10	PLY.10	90	0.25 CARBON	4	PLY DROP GUIDE CURVE 1	1
SEQUENCE.11	PLY.11	0	0.25 CARBON	4	PLY DROP GUIDE CURVE 1	1
SEQUENCE.12	PLY.12	0	0.25 CARBON	0	90 GUIDE CURVE	1
SEQUENCE.13	PLY.13	0	0.25 CARBON	0	STD 0 GUIDE CURVE	1
SEQUENCE.14	PLY.14	0	0.25 CARBON	2	SLIT 0 STRAIGHT GUIDE CURVE	1
SEQUENCE.15	PLY.15	90	0.25 CARBON	0	SLIT 0 STEERED GUIDE CURVE	1
SEQUENCE.16	PLY.16	0	0.25 CARBON	6	PLY DROP GUIDE CURVE 2	2
SEQUENCE.17	PLY.17	0	0.25 CARBON	0	PLY DROP GUIDE CURVE 2	2
SEQUENCE.18	PLY.18	0	0.25 CARBON	4	90 GUIDE CURVE	1
SEQUENCE.19	PLY.19	0	0.25 CARBON	6	STD 0 GUIDE CURVE	1
SEQUENCE.20	PLY.20	90	0.25 CARBON	4	SLIT 0 STRAIGHT GUIDE CURVE	1
SEQUENCE.21	PLY.21	0	0.25 CARBON	0	SLIT 0 STEERED GUIDE CURVE	1
SEQUENCE.22	PLY.22	0	0.25 CARBON	0	PLY DROP GUIDE CURVE 2	2
SEQUENCE.23	PLY.23	0	0.25 CARBON	2	PLY DROP GUIDE CURVE 2	2
SEQUENCE.24	PLY.24	0	0.25 CARBON	2	90 GUIDE CURVE	1
SEQUENCE.25	PLY.25	90	0.25 CARBON	0	STD 0 GUIDE CURVE	1
SEQUENCE.26	PLY.26	0	0.25 CARBON	2	SLIT 0 STRAIGHT GUIDE CURVE	1
SEQUENCE.27	PLY.27	0	0.25 CARBON	0	SLIT 0 STEERED GUIDE CURVE	1
SEQUENCE.28	PLY.28	0	0.25 CARBON	4	PLY DROP GUIDE CURVE 3	3
SEQUENCE.29	PLY.29	0	0.25 CARBON	6	PLY DROP GUIDE CURVE 3	3
SEQUENCE.30	PLY.30	90	0.25 CARBON	4	90 GUIDE CURVE	1

Figure A-4: Table of ply data including location in laminate, material, stagger and orientation

A.10 Explode the laminate to illustrate individual ply coverage

Design Step: 10

Design Phase: Detail Design

Task Objective: Explode the laminate to illustrate individual ply coverage

Task Description: Visualise the initial stacking sequence by plies

Design Objective: Move non-connected plies to different layers in the laminate where they improve continuity & move non-symmetry to centre of laminate

Manufacturing Objective: Fill gaps in the plies by moving material through the stacking sequence, strive for maximum symmetry, better ply continuity

Failure Mode: Sizing transposition incorrect

Effect(s) of Failure: Sub-optimal manufacturing solution

Root Cause: Excessive tailoring of the stacking sequences leads to poor ply continuity, as a result the deposition process is slowed down

Design Severity: Low

Manufacturing Severity: Low

Corrective Action: Pass design back to sizing if a symmetrical laminate cannot be achieved

A.11 Outline initial ply contours

Design Step: 11

Design Phase: Detail Design

Task Objective: Outline initial ply contours

Task Description: Automatically generate ply boundaries

Design Objective: Establish how clearance and ramp rates affect ply boundaries

Manufacturing Objective: Join small gaps in plies that have arisen from boundary conditions

Failure Mode (A): Ply boundaries too close together

Effect(s) of Failure (A): Deposition slowed excessively to perform boundary cuts and starts

Root Cause (A): Ply boundaries are sufficiently spaced in the grid until the ramping rules move them

Failure Mode (B): Unacceptable ply interleaving

Effect(s) of Failure (B): Poor interleaving in a ramp can cause delamination

Root Cause (B): Incorrect settings used for automatic ply generation

Design Severity: Medium

Manufacturing Severity: High

Corrective Action: If plies do not generate add ramp support fall back conditions, then re-check grid definition for complex geometry

A.12 Revise initial ply contours

Design Step: 12

Design Phase: Design for Manufacture

Task Objective: Revise initial ply contours

Task Description: Regenerate ply boundaries after stacking data has been updated

Design Objective: Capture any modifications to the stacking needed due to ply boundary issues

Manufacturing Objective: Join small gaps in plies that have arisen from boundary conditions

Failure Mode: Plies won't automatically generate

Effect(s) of Failure: Revision fails

Root Cause: Corruption of stacking data

Design Severity: Medium

Manufacturing Severity: Medium

Corrective Action: If plies do not generate add ramp support fall back conditions, then re-check grid definition for complex geometry

A.13 Account for minimum cut length

Design Step: 13

Design Phase: Design for Manufacture

Task Objective: Account for minimum cut length

Task Description: Check minimum cut length for all ply boundaries

Design Objective: Add material and re-shape areas of the ply boundaries that cannot be laid due to minimum course length

Manufacturing Objective: Ensure features that cannot be laid are removed

Failure Mode: Minimum cut length not achieved

Effect(s) of Failure: Unable to deposit fibres in key areas

Root Cause: Minimum cut length is required to feed material onto laminate. If the design requires shorter fibres, they cannot be deposited

Design Severity: High

Manufacturing Severity: High

Corrective Action: If angle cut wizard fails, manually add minimum cut length allowance to all affected ply boundaries

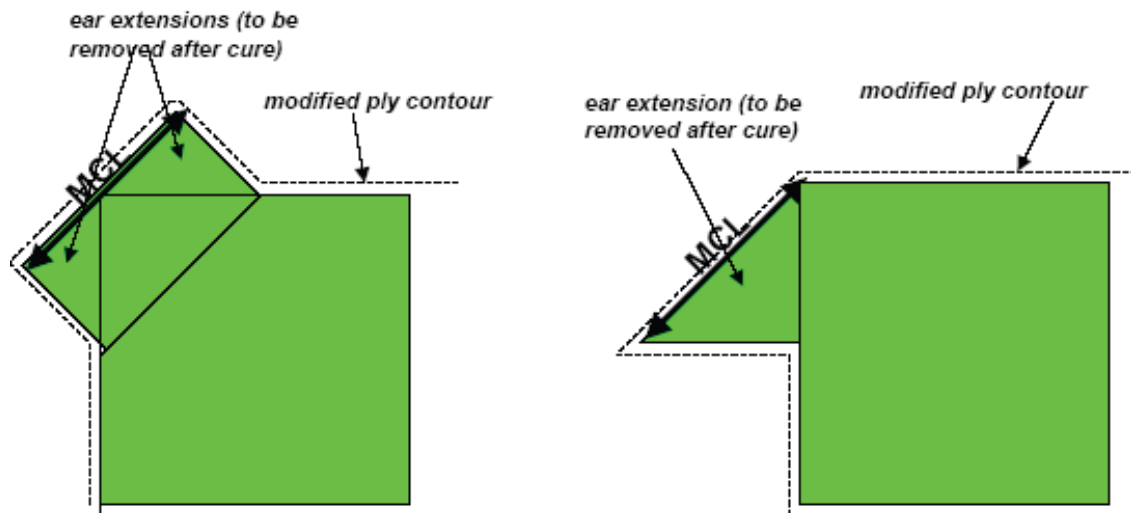


Figure A-5: Minimum cut length added to diagonal plies

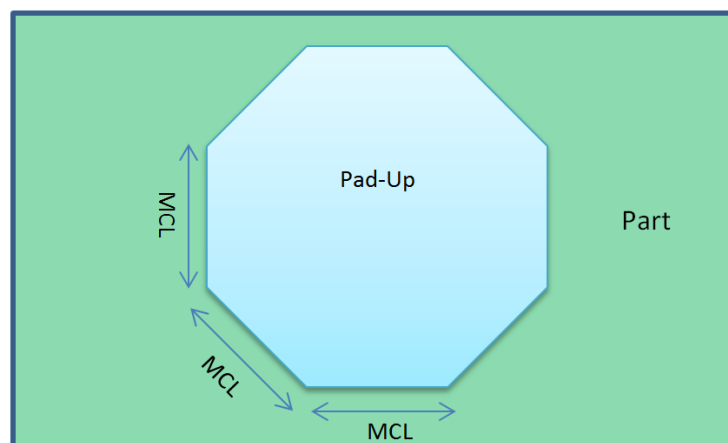


Figure A-6: An internal pad-up (locally thicker area) changes shape to an octagonal profile when minimum cut length is added. This may have been a round or square patch in the original design

A.14 Account for short fibres

Design Step: 14

Design Phase: Design for Manufacture

Task Objective: Account for short fibres

Task Description: Check any areas where short fibres might delaminate due to spring forces

Design Objective: Ensure additions are added to detail design model, particularly if they are inside the trim allowance

Manufacturing Objective: Short tapes over radii may spring off the laminate and need to be extended, sometimes this is not just in the trim allowance

Failure Mode: Short fibres not added in areas where tapes are in tension

Effect(s) of Failure: Fibres lift off laminate after deposition

Root Cause: The material's natural spring overcomes the adhesion over a short length. Extending the length increases adhesion

Design Severity: Low

Manufacturing Severity: Medium

Corrective Action: Liaise with design - it may not be able to add extensions without changing internal surface definitions and interfaces

A.15 Initiate guide curves

Design Step: 15

Design Phase: Design for Manufacture

Task Objective: Initiate guide curves

Task Description: Generate at least one guide curve per ply to base the machine trajectory on

Design Objective: Make guide curve angle as close to the design rosette for that ply

Manufacturing Objective: Follow a geodesic path to reduce defects in the deposited material - although this may invoke steering to recover rosette fibre angles

Failure Mode: Geodesic path exceeds material steering limit

Effect(s) of Failure: Material is deposited with defects

Root Cause: When steering radius is exceeded the material buckles and lifts from the laminate causing a defect

Design Severity: High

Manufacturing Severity: High

Corrective Action: Feed fibre angular deviation and steering values back to design so the stress model can be re-validated. In most cases, the design intent cannot be manufactured

A.16 Generate trajectories

Design Step: 16

Design Phase: Design for Manufacture

Task Objective: Generate trajectories

Task Description: Apply a deposition strategy to create the tape courses for each ply

Design Objective: Fill in the ply boundary with UD material

Manufacturing Objective: Generate coverage with acceptable gaps, overlaps, steering and angular deviations

Failure Mode (A): Trajectories diverge

Effect(s) of Failure (A): Fibres part leaving a gap, sometimes needing to be filled with an infill strip and convergence zones

Root Cause (A): Complex features cause geodesic fibre paths to be diverted

Failure Mode (B): Trajectories converge

Effect(s) of Failure (B): Fibres overlap or have to be terminated in a convergence zone

Root Cause (B): Complex features cause geodesic fibre paths to be diverted

Design Severity: High

Manufacturing Severity: High

Corrective Action: Failure to generate adequate coverage will need a convergence zone adding, a new ply boundary or a new geometrical surface - liaise directly with design

A.17 Governance: Fibre angles

Design Step: 17

Design Phase: Design for Manufacture

Task Objective: Governance: Fibre angles

Task Description: Check angular deviation

Design Objective: Try to maintain transposed angles from the rosette

Manufacturing Objective: Steer to maintain geodesic path to reduce tape defects

Failure Mode: Fibre angles exceed allowable tolerance

Effect(s) of Failure: Laminate has incorrect structural properties

Root Cause: Fibre trajectories diverge by angle greater than allowed

Design Severity: High

Manufacturing Severity: Low

Corrective Action: If fibre angle deviates too much from design intent revisit geometry with designer to reduce geodesic impact

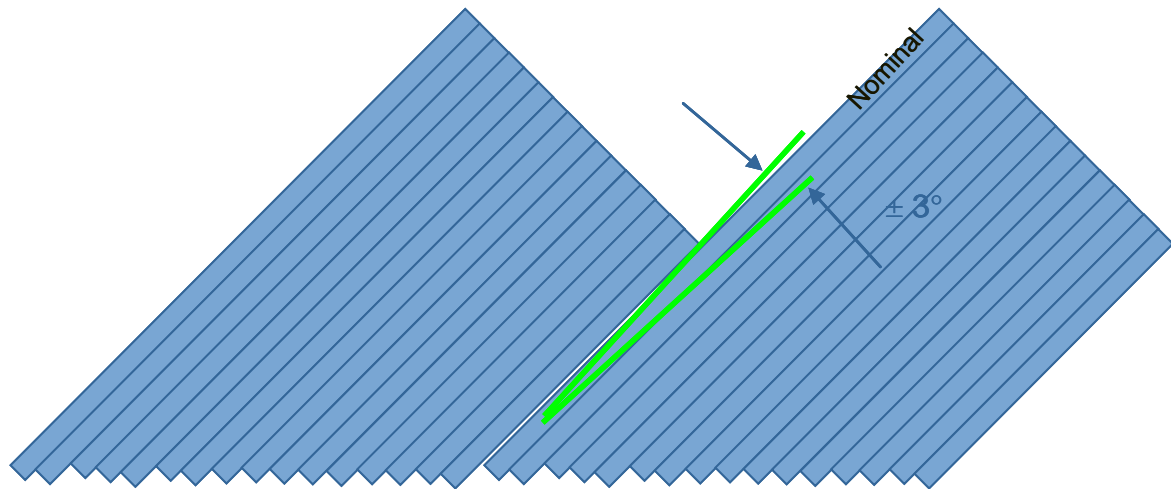


Figure A-7: Comparing a programmed trajectory to the design intent

A.18 Governance: Steering Radius

Design Step: 18

Design Phase: Design for Manufacture

Task Objective: Governance: Steering Radius

Task Description: Check radius of steering

Design Objective: Try to maintain transposed angles from the rosette

Manufacturing Objective: Steer fibre trajectories back to recover angular deviation caused by geodesic effects, but do not exceed minimum radius

Failure Mode (A): Material steering limit exceeded

Effect(s) of Failure (A): Material is deposited with defects

Root Cause (A): When steering radius is exceeded the material buckles and lifts from the laminate causing a defect

Failure Mode (B): Fibre angles exceed allowable tolerance

Effect(s) of Failure (B): Laminate has incorrect structural properties

Root Cause (B): Fibre trajectories diverge by angle greater than allowed

Design Severity: Medium

Manufacturing Severity: High

Corrective Action: If minimum radius exceeded, change starting and ending fibre alignments to reduce the degree of steering required



Figure A-8: Steering trials used to establish the steering limit radius for a specific material and AFP machine

A.19 Governance: Course Gaps

Design Step: 19

Design Phase: Design for Manufacture

Task Objective: Governance: Course Gaps

Task Description: Check course to course gaps

Design Objective: Try to keep individual gaps below 2mm, while not exceeding a cumulative gap width of 25mm in a 1m width of ply coverage

Manufacturing Objective: Distribute gaps to assist with steering

Failure Mode (A): Cumulative gap width limit exceeded

Effect(s) of Failure (A): Laminate weakened with potential for fibre volume fraction to be reduced

Root Cause (A): To cope with double curvature geometry, hybrid steering introduces gaps to recover fibre angles

Failure Mode (B): Individual gap width limit exceeded

Effect(s) of Failure (B): Laminate weakened with potential for fibre volume fraction to be reduced

Root Cause (B): Course to course gap combined with steering causes excessive gaps

Design Severity: High

Manufacturing Severity: High

Corrective Action: Liaise with design or reduce course width by dropping tows

A.20 Governance: Tow Gaps

Design Step: 20

Design Phase: Design for Manufacture

Task Objective: Governance: Tow Gaps

Task Description: Check tow to tow gaps

Design Objective: Reduce gaps where possible

Manufacturing Objective: Ensure individual and cumulative gap widths do not exceed design conditions

Failure Mode: Tow to tow gaps exceed limit

Effect(s) of Failure: Laminate weakened with potential for fibre volume fraction to be reduced

Root Cause: Course to course gap combined with steering causes excessive gaps

Design Severity: Medium

Manufacturing Severity: High

Corrective Action: Re-evaluate number of tows deposited and degree of steering if gaps are excessive

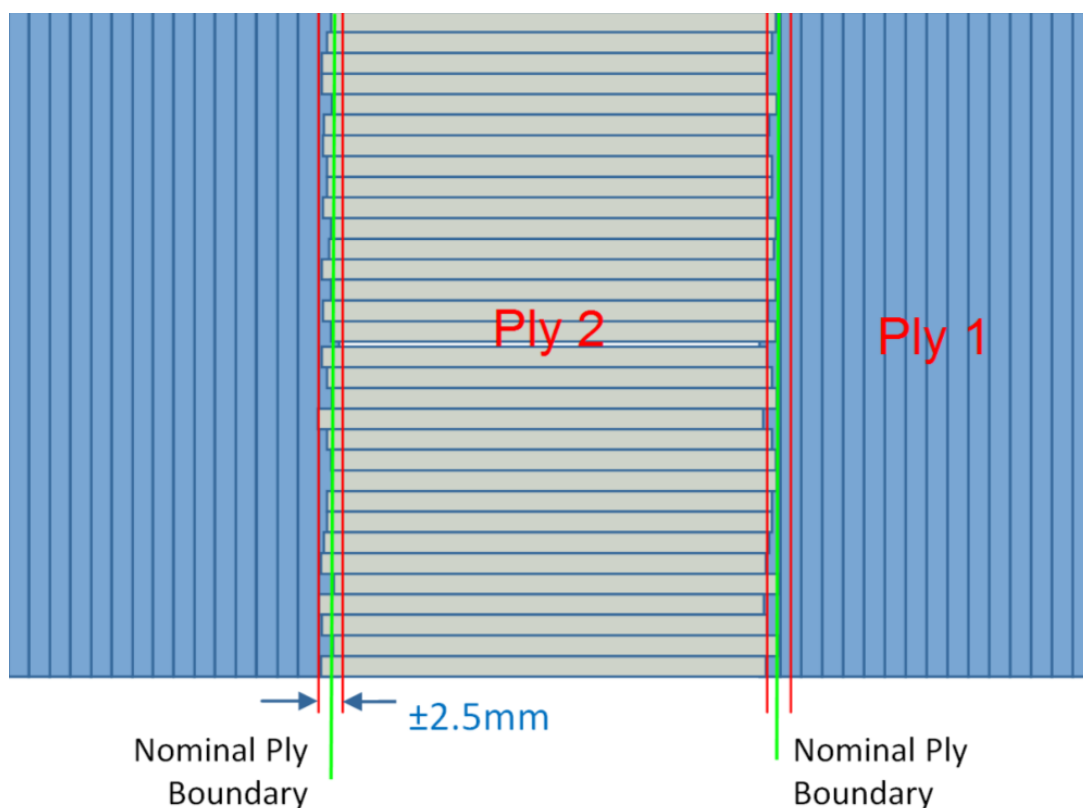


Figure A-9: Manufacturing tolerance associated with AFP process causing tow-gap defects

A.21 Governance: Overlaps

Design Step: 21

Design Phase: Design for Manufacture

Task Objective: Governance: Overlaps

Task Description: Check overlaps

Design Objective: Reduce overlap to design limits or lower

Manufacturing Objective: Try to avoid overlaps at all costs

Failure Mode: Overlaps exceed design limits

Effect(s) of Failure: Excess material thickness build up creates surface defects

Root Cause: Incorrect strategy for gaps and overlaps

Design Severity: High

Manufacturing Severity: High

Corrective Action: Overlaps will cause an increase in thickness and should be avoided is possible, if not - highlight impact on top surface to design

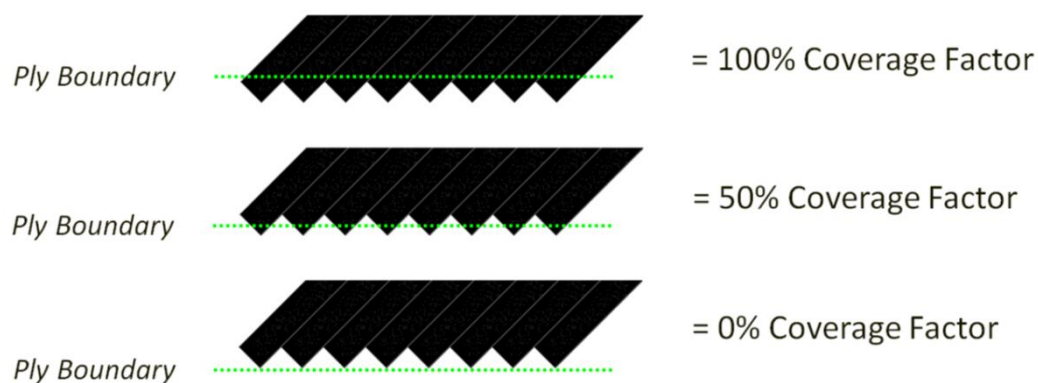


Figure A-10: Three default options for terminating an AFP course when it is not parallel or perpendicular to the ply boundary

A.22 Prevent alignment of gaps through laminate

Design Step: 22

Design Phase: Design for Manufacture

Task Objective: Prevent alignment of gaps through laminate

Task Description: Set stagger

Design Objective: Move the starting seed point of each ply so that they do not line up through the laminate

Manufacturing Objective: Set seed point as close to centre of largest geometrical feature, stagger from seed point

Failure Mode: Gaps or overlaps align through the z axis of the laminate

Effect(s) of Failure: Laminate weakened with potential for fibre volume fraction to be reduced

Root Cause: Course to course gap combined with steering causes excessive gaps

Design Severity: High

Manufacturing Severity: High

Corrective Action: Reiterate generation of coverage with new seed and stagger points until coverage is acceptable

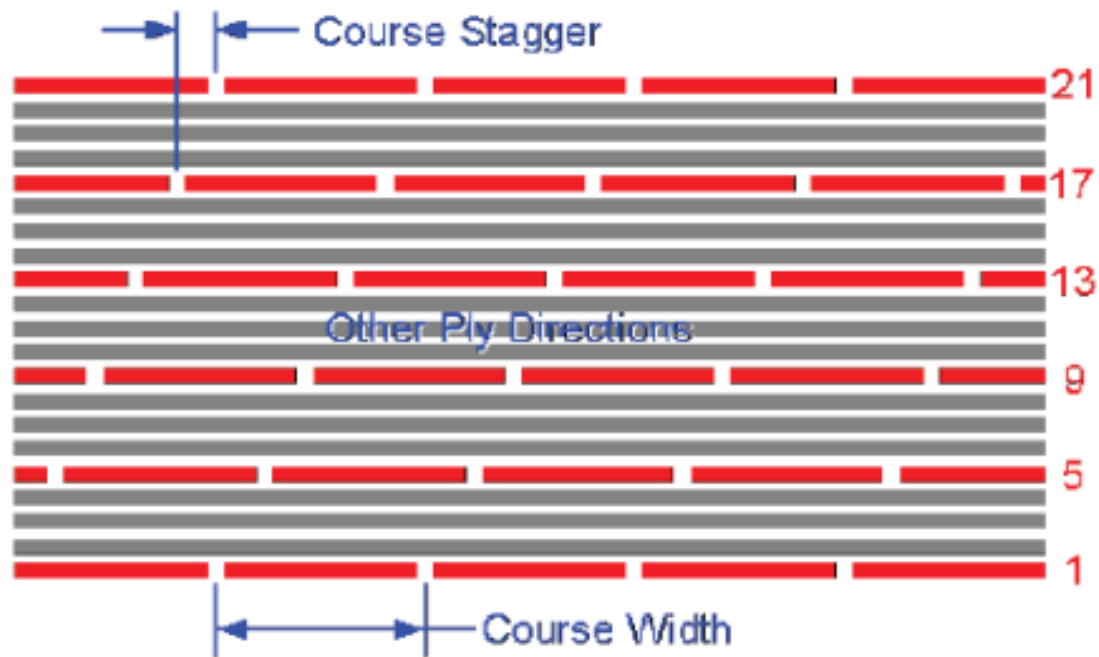


Figure A-11: Graphic representation of same ply orientation (red) being staggered throughout the laminate

A.23 Establish convergence strategies

Design Step: 23

Design Phase: Design for Manufacture

Task Objective: Establish convergence strategies

Task Description: Set boundary and convergence parameters

Design Objective: Transition ply coverage using original rosette where possible

Manufacturing Objective: Sectorise the ply coverage to allow acceptable convergence zones

Failure Mode: Fibre angles across component deviate from original rosette by more than the design allowable

Effect(s) of Failure: Laminate has incorrect structural properties

Root Cause: Fibre trajectories diverge by angle greater than allowed

Design Severity: High

Manufacturing Severity: High

Corrective Action: Liaise with design about acceptable convergence strategies

A.24 Identify areas of high consolidation (dry fibre)

Design Step: 24

Design Phase: Design for Manufacture

Task Objective: Identify areas of high consolidation (dry fibre)

Task Description: Highlight the areas in a structure where poor permeability is likely to occur

Design Objective: Maintain target fibre angles and a fibre volume fraction within design limits

Manufacturing Objective: Steer to introduce gaps in and around areas of high consolidation to allow resin to flow in areas of poor permeability

Failure Mode: Geometrical features over-consolidated

Effect(s) of Failure: For dry-fibre preforms, the feature permeability is too great to enable resin infusion and the component cannot be infused and cured

Root Cause: The fibres are over-compacted leaving insufficient air content, or permeability for the resin to flow through the preform

Design Severity: Low

Manufacturing Severity: High

Corrective Action: Poor permeability could cause a dry infusion, therefore more radical mitigations may be required in discussion with design

A.25 Generate tape coverage

Design Step: 25

Design Phase: Design for Manufacture

Task Objective: Create custom guide curves

Task Description: Create curves for steering and sectorisation if required

Design Objective: Align angle of curves to fibre angles in sizing

Manufacturing Objective: Control steering and gaps using a design controlled geometry

Failure Mode: Generated trajectories do not match fibre angles in sizing within acceptable tolerances

Effect(s) of Failure: Laminate has incorrect structural properties

Root Cause: Fibre trajectories diverge by angle greater than allowed

Design Severity: Medium

Manufacturing Severity: High

Corrective Action: Liaise with design if guide curves exceed angular deviation limits to have geometry changed accordingly

A.26 Check tape coverage in simulation

Design Step: 26

Design Phase: Design for Manufacture

Task Objective: Generate tape coverage

Task Description: Build ply coverage using guide curves for sectorisation and guides for each ply

Design Objective: None

Manufacturing Objective: Generate coverage with acceptable gaps, overlaps, steering and angular deviations

Failure Mode: None identified

Effect(s) of Failure: None identified

Root Cause: None identified

Design Severity: Low

Manufacturing Severity: Low

Corrective Action: Reiterate with different coverage parameters if results are not acceptable

A.27 Check simulation of tape coverage

Design Step: 27

Design Phase: Design for Manufacture

Task Objective: Check tape coverage in simulation

Task Description: Simulate the deposition of the tapes, adjusting for machine reach and component location where required

Design Objective: None

Manufacturing Objective: Check geometry and positioning of component is acceptable for AFP machine access

Failure Mode: Geometry prevents access of AFP head

Effect(s) of Failure: Material is deposited with defects (bridging) or the machine collides with laminate

Root Cause: Deposition machine cannot access the deposition surface

Design Severity: Low

Manufacturing Severity: High

Corrective Action: Re-position component in AFP cell or liaise with design to change geometry

A.28 Calibrate tool location

Design Step: 28

Design Phase: Design for Manufacture

Task Objective: Calibrate tool location

Task Description: Probe the location of the physical tool and re-run simulation

Design Objective: None

Manufacturing Objective: Position tool and re-check program as the reach of the machine will be slightly different from validation simulation

Failure Mode: AFP machine cannot reach component when positioned in real world

Effect(s) of Failure: When tool is positioned and program updated to account for real world environment, machine cannot reach/access component

Root Cause: Offline program assumes ideal position of tool. It is possible to position tool outside of machine reach for components close to the limits of the machine envelope

Design Severity: Low

Manufacturing Severity: Medium

Corrective Action: Physically reposition tool or change programming parameters for machine deposition strategy

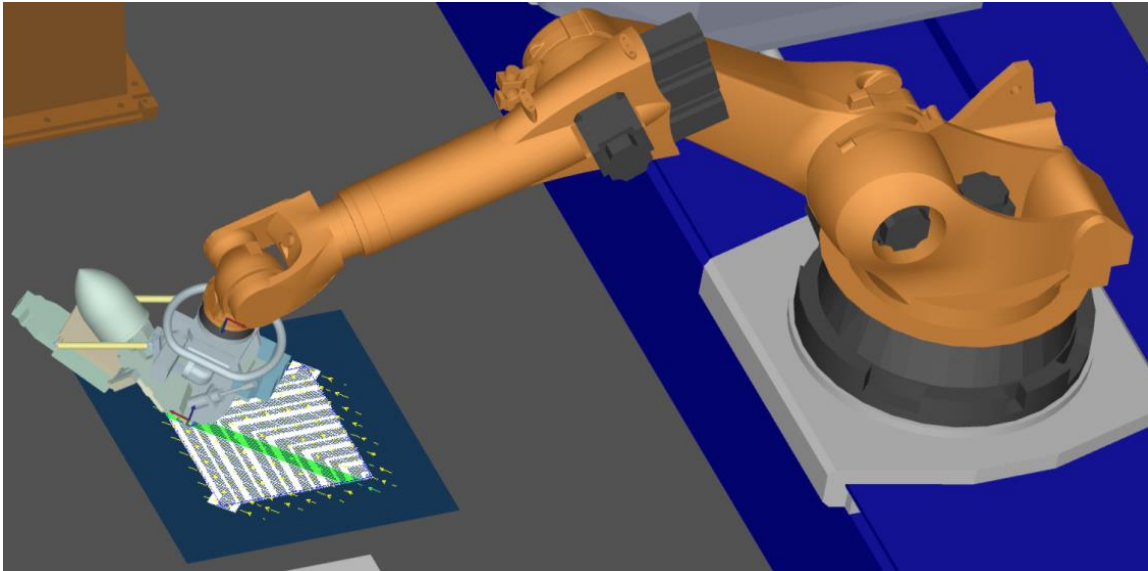


Figure A-12: Simulation testing reach of AFP machine for virtual tool. The program generated will only work if the AFP machine can reach the tool when it is datumed in the cell in real-world.